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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

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A sonic device for underwater sediment surveys. By E. C. LaFond, Robert S. Dietz, and J. S. Knauss

General aspects of detrital sedimentation in the geological basins of France. By André Vatan

Mineralogy of some Cretaceous sandstones from the Colorado Front Range. By August Goldstein, Jr.

Inclusions in the quartz of igneous and metamorphic rocks. By W. D. Keller and Romaine F. Littlefield

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THE ORGANIZATION OF SEDIMENTARY ROCKS[1]

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ABSTRACT

Attempted practical applications of existing classifications of sedimentary rocks commonly encounter difficulties and inconsistencies: (1) sediments normally unassociated during deposition are artificially grouped together; (2) inferences about environment, degree of tectonic influence, and other factors not everywhere legible in the rocks are required in differentiating major categories; (3) rocks of rare and common occurrence are given equal treatment; and (4) important rock types, such as shales and carbonates, are inadequately subdivided in contrast to attention accorded sandstone.

The proposed classification is designed for rapid determination of sedimentary rocks using the binocular microscope. The system of identification proceeds in regular order from characteristics which are most readily recognized to those which require more critical examination. Examples of specific conglomerate, sandstone, shale, and limestone varieties are listed and are arranged in groups to indicate their associations.

THE PROBLEM OF ORGANIZATION

The presumed random petrographic character and simple aspect of sedimentary rocks as compared to igneous or metamorphic types has delayed recognition of the complex, inter-related characteristics of sediments. The ease with which a sandstone or shale can be identified as opposed to the difficulty in recognizing, for example, a quartz diorite has masked the subtle complexity of sandstones and shales. Hence, despite Grabau's early proposal of an elaborate subdivision of sedimentary rocks, there has been little tendency to distinguish, and interpret the significance of, varieties of limestones, shales and sandstones. Except in the use of such adjectives as "argillaceous," "siliceous," or "calcareous," few descriptive petrographic terms have been used as refinements in characterizing a given sedimentary layer or a hand specimen; and little inquiry has been made into the repeated occurrences of certain rocks of surprisingly similar properties, but widely spaced both geographically and temporally.

Interdigitation of commonly occurring strata such as coal, underclay, and micaceous sandstone; red beds, evaporites, and dolomites; or dark gray shale and graywacke sandstone has long been recognized. Moreover, it is firmly established that certain associated sediments develop in restricted environments, and that all sediments respond to specific environmental controls. It is now becoming increasingly certain that as sedimentary rocks are studied in the subsurface, as well as in their area of outcrop, associations exist between specific sandstones, shales, and carbonate rocks; and, that some of these associations are mutually exclusive. Thus, the problems of stratigraphic correlation and reconstruction of the depositional conditions formerly existent within an area of changing sedimentary facies, necessitate further refinement in the existing classifications of sedimentary rocks. The importance of indicating unique petrographic types has been recognized by Tercier, Jones (1938), Krynine (1948), Pettijohn (1943) and the writers (1948). All have attempted to

[1] Presented before the Society of Economic Paleontologists and Mineralogists, St. Louis, March, 1949.

show that associated groups of sediments could be classified on the basis of their tectonic and depositional environments.

The objective of arranging sedimentary rocks into an organized system is to assemble into discrete groups all rocks of similar properties, of common association, and of common or related environments of deposition. Such groups or families must be distinct from one another and yet sufficiently general to include all sediments. Not only must the classification be designed to incorporate the features which are essential to all sedimentary rocks, but in assembling sediments into associated groups it should erect a framework for interpretation of sediment interrelationships. An organization so directed must necessarily be founded upon certain fundamental properties of the rocks. This is not a new concept, but the selection of which properties of sediments are the fundamental ones has been difficult. Confusion has arisen around the knowledge that the environment of deposition establishes the physical and chemical boundaries which in turn result in more obvious properties of the sediments. Hence, a number of systems of classification are based upon the limiting conditions of discrete environments of deposition as establishing the dominant controls on sedimentary types. This concept has virtue but difficulty arises in that the criteria by which specific environments are recognized in ancient sediments have not been clearly established, and in most instances, are based upon field characteristics or faunal evidence. Such criteria preclude recognition of the environment when hand specimens or crushed samples constitute all the available material. Under such circumstances classification of a rock becomes based upon inferences concerning the significance of certain observed features, or upon intuitive judgment. Obviously, if small fragments of a sedimentary rock are to be classified with the same degree of accuracy as large masses examined in the field, the system of classification and organization must be based upon fundamental properties inherent in small pieces as well as in large ones. That composition and texture are two of these properties has been proposed by Grabau (1904), Krynine (1948), Pettijohn (1949), and Shrock (1948). At the risk of some repetition, the writers propose to re-examine the prime factors which control sedimentary properties. It is hoped that such re-examination will yield a valid basis for a systematic organization and classification of sedimentary rocks.

THE CONSTITUENTS OF SEDIMENTS

All sediments consist of four significantly different constituents, These are: (1) Detrital particles which have been carried to the site of deposition and under the prevailing energy state of the transporting medium settled downward to the depositional interface. (2) Inorganic salts precipitated from solution at or above the depositional interface and incorporated as an integral part of the accumulating sediment. (3) Inorganic salts precipitated on the existing grains or crystals, or in the interstitial spaces. (4) Materials produced by organic activity. Any of these may constitute a primary rock type or be fragments which are a part of the accumulating sediment.

Each of the above constituents contributes to the petrography or texture and composition, of the resulting sedimentary rock. In certain sediments the detrital matter greatly overshadows the other constituents in amount and, hence, the petrographic characteristics are controlled by the properties of this detrital material. In other sediments, however, the precipitated salts or organic matter dominate and detrital matter is minor. Although complete intergradation exists between the two extreme rock types, the very large majority of sediments are dominated by one or the other extreme. Thus, two large kingdoms are established. One of these can be called the allochthonous sediments and represents those in which the detrital particles derived from outside the depositional medium constitute the major part of the sediment.

Such sediments are commonly designated as the detrital or clastic rocks. Autochthonous sediments constitute the other kingdom. In these the preponderance of material is derived from within the depositional medium, i.e., is representative of those in which the precipitated salts or organic materials dominate. These because of their mode of origin are also called chemical or non-clastic rocks.

The allochthonous sediments.—Inasmuch as allochthonous sediments are assemblages of fragments, they constitute a continuous series ranging from those whose particle diameters are extremely large to those whose particle diameters are extremely small. This range in size of particles has been grouped into the familiar series of class sizes recognized as boulders, cobbles, pebbles and so forth (Udden, Wentworth, Atterberg and others). The occurrence of particles of similar dimensions is controlled by the degree of turbulent energy in the transportational medium, and by the settling velocity of the particles. When the degree of turbulence is low, and the supply of debris is constant, the settling velocity is the dominant dynamic factor which controls the parameters of the accumulating particles; hence, particles of similar size, shape, and density may occur in a single bed. As turbulence decreases, particles of smaller dimensions are deposited, and gradation upward of material from coarse to fine is observed in the accumulated sediment. Under some conditions of turbulent flow, fine material may be winnowed from a deposit, leaving behind coarser particles of uniform shape and density; or such coarser particles may settle from the load. Under the first and third sets of conditions the final sediment will tend to be uniform in size distribution and interstitial matter will be absent, or small in amount. Under the second set of conditions the texture of the resulting sediment will contain coarser fragments in a finer grained matrix, and show graded bedding. Thus, degree of turbulence associated with a given state of flow, and the settling velocities, are the prime influences on the texture of the accumulating allochthonous sediment. Moreover, these controls also exert an influence on the bulk composition of the sediment by segregating particles of similar mineralogy.

Among very coarse sized materials, such as pebbles, the influence of turbulent energy and settling velocity on the composition of the accumulating sediment is minor, although important in controlling texture. Limestone and granite fragments of the same size settle at about the same rate. In the finer sizes, however, where the grains are monomineralic, the tendency to concentrate minerals of similar density and shape becomes pronounced. This process accounts for the distinction between shales and sandstones. Quartz, feldspar, and hard minerals of low cleavage tendency and large crystal size tend to overshadow all other minerals in the common sandstones. The clay minerals, micas, and soft minerals of good cleavage and small crystal size, are the preponderant minerals of shale.

Variations in the turbulence energy of the depositional medium tend to increase the standard deviation of the size distribution of accumulating debris, so that a wide range of particle sizes is deposited. The fine material, which may occupy interstices, or form the bulk of the deposit, is the matrix. The matrix is most readily recognized in sediments with strongly bimodal size frequency distributions. Generally, allochthonous materials contain appreciable amounts of matrix, but some contain only minor amounts, and the latter suggest uniform conditions in the depositional medium.

In addition to particles and matrix, a third constituent of sediments is chemically precipitated material which forms the cement. It may be difficult to distinguish between matrix and cement; however, the former is chiefly of allochthonous nature while the latter is chemically derived. The cement may be simply a filler between the grains, or it may be in optical orientation with the grains. Ob-

viously, the relative proportions of particles, matrix, and cement, control the textural aspect of the rock. Likewise, the over-all petrography is a function of the relative abundance and chemical composition of these three constituents.

Where shells or other fossils are incorporated as part of an allochthonous sediment, they must be omitted from evaluations of texture, since it cannot always be determined whether they were part of the transported load. Moreover, since they originate within the medium in which they are deposited they cannot by definition be considered as allochthonous material.

The autochthonous sediments.—The chief component of autochthonous rocks is the salts precipitated from solution. Nevertheless, every chemical sediment may be subject to reworking within the medium in which it was deposited. The fragments of reworked material have the characteristics of detrital particles in that they are transported to other sites of deposition where they are segregated by their settling velocities. With sediments of such origin there is little distinction between the composition of the particles, matrix, and cement; yet the over-all aspects are similar to those of the allochthonous sediments, in that they show crossbedding, etc.

Autochthonous sediments which are not reworked constitute the main varieties. In these the texture is an interlocking network of crystals. Particles other than the interlocked crystals may be extraneous allochthonous debris, or local rock and fossil fragments. The latter are frequently intergrown crystallographically with the crystalline mass, and in thin-section the two are often distinguished with difficulty.

The differences in textural aspects and mode of accumulation of autochthonous rocks were recognized by Grabau (1904), who classified such sediments as both detrital and non-detrital, on the basis of cross-bedding and other structures. It is thus apparent that a logical classification of autochthonous sediments requires a clear distinction between rocks designated on the basis of the properties of particles, cement, and matrix, on one hand and on the textural character of the crystalline mass on the other.

Inasmuch as the detrital material of allochthonous sediments is derived from outside the medium of deposition, and the autochthonous rocks are precipitated from the depositional medium itself, a certain degree of mixture must occur in most instances. If allochthonous debris dominates, the sediment acquires the texture and over-all composition of the allochthonous rocks, and the dilution of such material by the autochthonous cement may range from small to about half of the total material. In such instances the autochthonous material constitutes the matrix in which the detrital particles are imbedded. In other cases the percentage of autochthonous material may be so small that it fails to appear as a matrix but can only perform the duties of a cementing agent. Where the autochthonous cement dominates, the detrital fragments become imbedded in increasing amounts of autochthonous matrix. Such detrital debris constitutes the "impurity" within a rock whose over-all composition and appearance is characteristic of chemical rocks. The admixed detrital matter, however, modifies the over-all aspect and contributes to the establishment of certain clearly defined sub-textural types.

Despite the occurrence of a continuous series between allochthonous and autochthonous sediments, the most commonly occurring rocks distinctly belong to one type or the other, and the rare sediments are those which are hybrids and classified with uncertainty.

ENVIRONMENTAL AND TECTONIC CONTROL OF DEPOSITION

The reader is familiar with the concept that in the course of several cycles through which a sediment may pass, each environment to which it is subjected alters the material in some fashion. Obviously, this applies chiefly to detrital sediments, since those autochthonous

sediments which are precipitated directly from the depositional medium and buried, can be exposed to only one environment of deposition. The length of time of exposure to the environment of deposition is also of prime importance. Long exposure to the final depositional environment tends to erase most of the characteristics imprinted upon the particles by previous environments, and to endow it with characteristics of this final environment. On the other hand, if the sediment is buried soon after arrival at a depositional site, heterogeneity of texture and composition prevails. Rapidity of burial is, therefore, a control upon the environmental influence. In general, rapidity of burial is controlled by contemporaneous tectonism of the depositional site.

Tectonism as a controlling influence on sedimentation is being increasingly emphasized. This emphasis centers about the degree of tectonic activity obtaining within the depositional environment. If all sites of major deposition of sediments are assembled according to the tectonism of the region receiving the sediments, they can be considered as occurring under three main types.

The first of these is the area of dominantly neutral tectonic activity associated with widespread shelf conditions. Deposition on shelves is characterized by extensive reworking and winnowing, and by the accumulation of a relatively thin veneer of sediments. The second tectonic unit is the intracratonic basin. This differs from the shelf by its increasingly negative character, by the accumulation of sediments in considerable thickness, and more rapid burial of sediments after varying degrees of exposure to the depositional environment. The third tectonic unit is the geosyncline, in which deposition is characterized by rapid burial under conditions of strong negative tendency, with concomittant rapid passage of particles through the depositional interface, and limited influence by the sedimentary environment.

Each of these tectonic conditions produces typical associations of sediments. The reader is referred to Dapples, Krumbein, and Sloss (1948) for details.

CLASSIFICATION OF SEDIMENTARY ROCKS

Classification based on environments of deposition.—Early recognition of the large number of distinct domains in which sediments accumulate led naturally to grouping them under continental and marine environments. The latter were further subdivided largely on the basis of bathymetric zones established in the light of the known distribution of modern organisms. It is true that the ancient sediments possess many bulk attributes present in debris now accumulating, and in consequence the environment of deposition of many ancient deposits can be recognized. It is equally true, however, that the environments of deposition of many of the ancient sediments cannot be recognized. This paradox arises from two conditions which are inherent in the problem. First, the criteria for the recognition of environments in ancient deposits have not been conclusively established, and secondly, the imprint of the environment of deposition may not be clearly impressed upon the sediment. Such is particularly the case when only small samples of the sediment are available and the field relationships cannot be observed. In this case the geologist is required to make his entire interpretation on the basis of the texture and composition of the rock fragment. If the environment cannot be inferred from the texture and composition then no available means of determining the genesis remains. Classification upon the basis of environment is under such circumstances reduced to an arbitrary decision wherein the sediment in question may be placed in a group of rocks in which it might not properly belong.

The proposed classification.—Difficulties involved in classification of rocks based upon the environments of deposition leave no alternative for the present except to erect an organization based upon certain characteristics present in sedi-

mentary rocks of all varieties, and observable in small fragments as well as in the field. Data other than those which for certain specimens have been gathered in the field are restricted to the petrographic aspects of the rock in question. These differences are sufficiently distinct to permit the recognition of many varieties without recourse to inferences regarding source, environment, tectonism, etc.

The proposed system is designed with certain primary objectives in view; (1) to organize sediments into associated and intergrading groups, (2) to establish a system of nomenclature which permits recognition of the group to which a sediment belongs, (3) to provide a system of rapid identification of sediments based upon observable fundamental properties. (4) Finally, to build the identification system as much as possible around simple tests and the binocular microscope in order to permit rapid identification of cuttings, crushed samples, and hand specimens. It is recognized, however, that such simple tests cannot substitute for the accuracy of thin-section examination with the petrographic microscope which must be relied upon in numerous instances. Nevertheless, the enormous amount of drill cuttings which must be examined daily makes it imperative that some rapid system of classification be employed.

The scheme of identification used is based upon the fundamental attributes of the major sedimentary rocks as discussed in earlier paragraphs. The first breakdown (see table A) is into rocks which can be immediately recognized as belonging to a major class and, those which require further tests. Item I of table A is to be used when the bulk nature of the rock is revealed by inspection, i.e., the rock is identified as a sandstone, or a shale, and so forth. The number of rocks so identified varies with the skill and experience of the observer, but even to the trained eye some of the hybrid rocks cannot be placed in their major group without additional tests. Item II of table A is designed to screen such rocks into their proper major groups. This is done by classifying the rock as fragmental, dense, or crystalline. Varieties of chemical rocks are distinguished from allochthonous rocks on the basis of their composition. Inasmuch as the large majority of chemical rocks are carbonates, sulphates, chlorides, phosphates, and silica, simple hardness and effervescence tests are sufficient for further subdivision.

Actual organization of the sedimentary rocks into associated groups is accomplished in tables 1 through 4. Each of these is so arranged that the fundamental properties bearing on the composition and texture of the rock are employed, beginning with the most obvious features and proceeding to those which are less obvious or require special investigation.

THE COMMON ROCK FAMILIES

Conglomerates and breccias.—Table 1 is the organization of conglomerates and breccias. These differ from finer grained clastic rocks in texture and grain size rather than in composition. By custom, distinction between conglomerates and sandstones is drawn on a limiting diameter of 2 mm. Just what proportion of the particles must exceed 2 mm before the rock can be called a conglomerate is uncertain (Pettijohn 1949). The bimodal character of the particle size distribution, typical of most clearly defined conglomeratic textures, may also be present when the particles are less than 2 mm in diameter. In short, there exists no precise method, nor any generally agreed upon boundary, for distinguishing between conglomerates and sandstones. With this point in mind the writers have arbitrarily elected to define the limits between sandstones and conglomerates on the basis of a diameter of 4 mm for the largest particles. A rock in which the largest particles within the sample under examination exceed 4 mm is a conglomerate. Selection of this dimension in preference to smaller values used in other classifications is based upon two textural aspects of conglomerates; (1) particles larger than 4 mm possess the shape characteristics and the petrography

TABLE A.—*Preliminary grouping of sedimentary rocks*

I. ROCK TYPE DETERMINED BY DIRECT INSPECTION
- A. *Conglomerate or breccia*
  Rock must consist of individual rock fragments which are not exclusively fossil remains; size of the largest rock particle must exceed 4.0 mm in diameter. If the roundness index exceeds 0.2 the rock is classified as a conglomerate, if less it is classified as a breccia.
  1. Composed of many varieties of rock fragments—see table 1
  2. Composed of few varieties of rock fragments
     a. preponderance of igneous or metamorphic rocks—see table 1
     b. preponderance of sedimentary rocks—see table 1
- B. *Sandstone*
  1. Largest particles exceed 4.0 mm in diameter—see item IA above
  2. Largest particles less than 4.0 mm in diameter
     a. particles scratch steel—see table 2
     b. particles do not scratch steel—see table 4
- C. *Siltstone and shale*
  1. Largest particles range from $\frac{1}{8}$ to 1/100 mm in diameter
     a. field characteristics those of siliceous sandstone—see table 2
     b. contain local siliceous sandstone lenses—see table 2
     c. interbedded with siliceous sandstones in small units—see table 2
     d. field characteristics those of shales—see table 3
     e. contain local shale lenses—see table 3
     f. interbedded with shales or carbonates in small units—see table 3
  2. Largest particles range up to 1/100 mm—see table 3
- D. *Limestone or dolomite*
  Rock effervesces freely, or when powdered, with dilute HCl—see table 4
- E. *Evaporite*
  Hardness less than 3—see table 4
- F. *Chert or flint*—see table 4
- G. *Coal*—not classified

II. ROCK TYPE DETERMINED BY SPECIAL TESTS
- A. *Rock is clearly particulate or fragmental, large particles* $> \frac{1}{8}$ *mm diameter*
  1. Particles and matrix effervesce readily with dilute HCl—see table 4
  2. Particles and matrix effervesce with dilute HCl when powdered or scratched—see table 4
  3. Particles do not effervesce with dilute HCl, matrix may or may not effervesce
     a. particles readily scratched with a needle but not carbonaceous—see evaporites table 4
     b. particles not scratched with needle—see sandstone or siltstone table 2
- B. *Rock is particulate or fragmental but particles range from* $\frac{1}{8}$ *to 1/100 mm in diameter*
  1. Little or no effervescence with dilute HCl
     a. dominance of particles over matrix—see siltstone table 2
     b. dominance of matrix over particles—see table 3
  2. Pronounced effervescence with dilute HCl when scratched—see table 4
- C. *Rock is particulate but particles* $< 1/100$ *mm in diameter*
  1. Little or no effervescence with dilute HCl—see table 3
  2. Pronounced effervescence with dilute HCl when scratched—see table 4
- D. *Rock is dense or finely crystalline*
  1. Effervesces readily with dilute HCl (limestone)—see table 4
  2. Powder effervesces with dilute HCl (dolomite)—see table 4
  3. No effervescence with dilute HCl
     a. flakes when scratched with needle—see tables 3 and 4
     b. clay shreds when scratched with needle—see table 3
     c. microlaminated, powders when scratched with needle—see table 3
     d. brown carbonaceous powder when scratched with needle—see table 3
     e. not scratched with needle—see tables 2 and 4
     f. coal—not classified
- E. *Rock is moderately or coarsely crystalline*
  1. Rock scratches steel
     a. no effervescence with dilute HCl—see table 2
     b. dominance of crystals effervesce freely, or when powdered with dilute HCl; rock can be scratched, but some crystals will scratch steel—see table 4
  2. Rock does not scratch steel
     a. no effervescence with dilute HCl (evaporites)—see table 4
     b. crystals effervesce readily, or when powdered, in dilute HCl—see table 4

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(i.e., polymineralic) of typical pebbles, whereas smaller particles have attributes of sand grains, (2) prominent bimodal size distribution is more commonly observed in rocks where the coarseness exceeds 4 mm than in those of 2 mm or less. Further restriction in defining conglomerate arises from the fact that distinction on the basis of particle size alone is not satisfactory, since the over-all aspect of the conglomerate may be produced by shells or fragments of shells of organisms in an otherwise finer-grained matrix. Although certain of the reef-flank rocks have the characteristics of conglomerates or breccias it is not the intent to classify as such those rocks in which fossils constitute the large particles.

Distinction must also be drawn between conglomerate and breccia. Here again the difference is textural and depends upon the angularity of the fragments, which by common agreement must consist of angular fragments to classify the rock as a breccia. Nevertheless, the degree of angularity is not expressed quantitatively, and hence no precise value of the degree of angularity necessary to constitute a breccia exists. The writers have compared the roundness of fragments in a number of specimens generally agreed to be breccias with the roundness index chart (Krumbein 1941) and noted that a roundness of 0.2 represents the demarcation between typical breccias and conglomerates. This value (0.2) is arbitrarily selected as the limiting roundness of particles in breccias, and rocks in which 50 per cent or more of the fragments have a roundness less than 0.2 are classified as breccias.

Table 1 is so arranged that the method of classification proceeds from rock characteristics most easily recognized or observed, to features which require more critical observation. After the rock is recognized as a conglomerate the composition of the fragments is the next most obvious characteristic. Conglomerates or breccias can be crudely divided into certain primary groups depending upon whether they consist of pebbles of one, few, or many petrographic types. Each of these can be further subdivided on the basis of detailed petrography.

The second major feature recognized in the very coarse clastics is the matrix in which the fragments are embedded. In table 1 this item is examined after the conglomerate (or breccia) has been classified on the basis of the contained rock fragments. The matrix is examined in terms of its hardness, reaction to HCl, and, finally, its composition. At this stage the rock is to all intents and purposes classified, but further distinction is drawn on the basis of the cementing materials, which permits refinement in characterizing certain types. Each variety is then given a simple, but definitive, name which is selected to generally reveal the petrography of the rock. The examples listed in the last column of table 1 suggest the variety of rock types which may be encountered in each category but no attempt is made to prepare an exhaustive listing.

Micro-conglomerates, sandstones, and siltstones.—Table 2 shows the classification of rocks whose general aspects are those of sandstone. As in table 1 the arrangement proceeds from the most obvious and readily observed features to those which require refinement of observation. Apart from its particular texture the most obvious feature of the sandstone is its petrography. The rocks are arranged in three groups, those in which quartz is dominant, and those in which several minerals are present in significant amount. This arrangement is devised for allochthonous sandstones. Carbonate "sands," such as dolomite rhombs, are included, but may be more appropriately classified in table 4.

The second obvious feature of sandstone is color, which is generally a reflection of the bulk mineralogy. It is, therefore, useful in roughly defining groups of sandstones. Reaction to HCl reveals the amount of carbonate matrix or cement present and serves to distinguish between certain quartzose sandstones whose mineralogy is otherwise similar.

TABLE 1.—*Megascopic conglomerates and breccias*
(see table A for distinction between conglomerates and breccias)

Rock Particles	Composition	Matrix	Cement	Examples

(see table A for distinction between conglomerates and breccias)

	Composition					Examples
	Rock Particles	Matrix			Cement		
		Hardness	Reaction to HCl	Composition	Reaction to HCl	Composition	
PRIMARILY ONE VARIETY	Quartz, quartzite, chert, flint and some carbonate	scratches steel	none to moderate	generally large amounts, quartz sand dominant, also calcareous sand	none to strong	siliceous common, calcareous less common	Quartz pebble conglomerate or breccia Chalcedonic quartz pebble conglomerate or breccia Quartzite pebble conglomerate or breccia Chert pebble conglomerate or breccia
	Quartz, chert, flint, iron oxides		none	fine particles of iron oxide, quartz, and clay	none or very slight	ferruginous or siliceous	Ferruginous chert pebble conglomerate or breccia Iron oxide pebble conglomerate or breccia Quartz-pebble conglomerate or breccia
	Limestone, dolomite, siderite	does not scratch steel	generally strong to moderate when powdered	calcareous or argillaceous, generally in small amounts	generally strong to moderate	generally calcareous, but may be siliceous	Limestone conglomerate or breccia Dolomite conglomerate or breccia Siderite conglomerate or breccia
	Limestone, dolomite, siderite, shale in thin fragments			calcareous or argillaceous in large amounts			Flat pebble or edgewise conglomerate or breccia
	Limestone, dolomite, often large in size, associated with much fossiliferous fragmental material			calcareous or argillaceous generally in small amounts, often a calcareous sand	generally indistinguishable from matrix		Reef flank conglomerate or breccia Fossiliferous-fragmental conglomerate or breccia (These may be better classified as carbonates. See table 4)
	Limestone or dolomite, may have gypsum or anhydrite, some red shale			calcareous			Solution breccia
	Shale	may or may not scratch steel	generally none to slight	argillaceous or sandy	none to slight	siliceous, ferruginous or slightly calcareous	Shale pebble conglomerate or breccia
FEW VARIETIES	Plutonic igneous and metamorphic	scratches steel	none to slight	ranges from small to large amounts; feldspathic sand dominant		siliceous, ferruginous, rarely calcareous	Granite-schist conglomerate or breccia Granite-slate conglomerate or breccia Diorite-gneiss conglomerate or breccia Gabbro-schist-calcareous conglomerate or breccia
	Dominantly effusive, and basic igneous rocks			large amounts of sand size, eruptive rock particles, mica, chlorite and clay			Basalt-andesite agglomerate Basalt-scoria agglomerate Rhyolite-andesite agglomerate
	Chiefly granite, some feldspar (alkaline) crystals		reaction common	feldspar, mica, quartz, moderate amounts of clay	none to moderate	generally siliceous, calcareous less common	Granite wash conglomerates or breccia Arkose conglomerate
MANY VARIETIES	Igneous and metamorphic more abundant than sedimentary	scratches steel	some reaction common	quartz dominant, feldspar, mica, rock fragments, chlorite; chiefly sand grain size, some clay	none to moderate	siliceous, ferruginous, carbonate	Granite-schist-dolomite graywacke conglomerate or breccia Diorite-slate-sandstone graywacke conglomerate or breccia Granite-gneiss-schist graywacke conglomerate or breccia
	Sedimentary more abundant than igneous or metamorphic			quartz dominant, rock particles, some feldspar, very small quantities of clay	none to strong	carbonate common, siliceous or ferruginous	Limestone-quartzite-granite quartzose conglomerate Sandstone-basalt-granite quartzose conglomerate
	Wide range of varieties, wide range in particle size		strong reaction common	dominantly clay dimension but wide mineral range; may also be sandy with wide mineral range	commonly strong	carbonate common, also siliceous	Tillite

TABLE 2.—*Microconglomerates, sandstones, and massive siltstones*

Appearance		Reaction to HCl	Composition	
Bulk	Special		Particles	Matrix
Monomineralic (quartz >90%) +detrital chert	very light colors predominate	none to slight	quartz, light chert	generally none, minor amounts of silt or clay
Quartz+detrital chert dominant	red or brown colors	generally none	quartz with iron oxide coating	finely divided iron oxide
	green colors		quartz, glauconite	minor, finely divided quartz and glauconite
	gray colors, muscovite flakes	none to slight	quartz, muscovite concentration on bedding surfaces	minor amounts, chiefly quartz silt, clay minor
	gray colors, small amounts feldspar		quartz and mica dominant, feldspar minor, coal fragments common	moderate amounts, chiefly quartz silt, clay moderate, some carbonaceous matter
	gray colors, moderate amounts feldspar		quartz, feldspar, minor biotite and muscovite	moderate amounts, chiefly quartz silt; clay and iron oxide minor
				minor amounts of matrix
Other mineral species abundant (except carbonates or sulphates)	"salt and pepper" gray color, black chert prominent	generally slight to moderate	quartz, black chert predominate; mica, pyribole, glauconite less prominent	moderate amounts; quartz, mica, silt and clay in equal proportions
	tuffaceous, laminated (porcellanite)	generally none	feldspar (Ab 80%), glass fragments and quartz (igneous) prominent; mica minor	moderate amounts, fine felt of glass and feldspar
	pink gray or red gray colors, generally coarse grained	slight to moderate common	feldspar (>25%), quartz, mica less prominent	minor to moderate amounts, chiefly clay, some quartz silt, mica, and iron oxides
	medium gray colors		quartz (all varieties), rock fragments, mica, small amounts of feldspar	moderate to large amounts, chiefly clay, mica, chlorite
	medium gray colors "salt and pepper"	none to moderate	plagioclase, pyribole, mica, and black chert dominant; moderate amounts quartz, chlorite, and rock fragments	
	dark gray colors	none	quartz (all varieties), mica, pyribole, rock fragments and chlorite	
Carbonate particles dominant (See table 4)	crystals, fossil fragments or particles, with or without noticeable matrix	strong, especially of powder	calcite, dolomite, rarely gypsum	calcite, dolomite, clay, etc.

Refinement of sandstones into quartzose, subgraywacke, arkosic, and graywacke types is based upon the composition of the particles, of the matrix, the cement, and the accessory minerals. In many instances this can be done without resort to thin-section examination or crushing and extracting the accessory minerals; but thin-section examination provides the most reliable method of identification.

Each sandstone type is named in accordance with the characterizing mineral species and the over-all rock type. This permits the inclusion of additional sandstone varieties which have not been previously distinguished, particularly among subgraywackes and graywackes. Inasmuch as the boundaries of sandstone types have not been clearly established, some confusion is to be expected in distinguishing certain subgraywackes

TABLE 2.—*Microconglomerates, sandstones, and massive siltstones*

Composition		Examples	Group Name
Cement	Accessory Heavy Minerals		
eous, rarely calcareous, of- poorly cemented	few, very stable suite	Pure quartz sandstone or siltstone	Quartzose sandstones or siltstones
iginous, siliceous, gypsifer-	few, stable suite	Quartz-iron oxide sandstones or siltstones	Quartzose sandstones or siltstones
eous, rarely calcareous		Quartz-glauconite sandstones or siltstones	Quartzose sandstones or siltstones
eous to slightly calcareous, n poorly cemented	dominantly stable suite	Quartz-muscovite sandstones or siltstones	Quartzose sandstones or siltstones
eous to slightly calcareous, rally moderate	calcareous common, also siliceous, moderate to well cemented	Quartz-mica-feldspar subgraywacke sandstones or siltstones Quartz-mica-carbonaceous subgraywacke sandstone or siltstone	Subgraywacke sandstones or siltstones
		Quartz feldspar subgraywacke sandstone or siltstone (< 25 % feldspar)	Subgraywacke sandstones or siltstones
		Arkose (< 25 % feldspar) Quartz-feldspar sandstone or siltstone (< 25 % feldspar)	Arkosic sandstone Quartzose sandstone
areous common, also sili- s, moderate to well ce- ted		Quartz-black chert subgraywacke sandstone or siltstone	Subgraywacke sandstone or siltstones
eous	rare, suite unstable, some pyrite	Sodic feldspar-glass subgraywacke sandstone or siltstone	Subgraywacke sandstones or siltstones
areous common, also sili- s	moderate amounts, unstable suite	Gray arkose Pink arkose Granite wash arkose (thin sheets)	Arkosic sandstone or siltstone
	moderate amounts, unstable suite	Quartz-mica graywacke sandstone or siltstone	Graywacke sandstone or siltstone
eous to slightly calcareous	moderate to large amounts, unstable suite	Calcic feldspar-pyribole graywacke sandstone or siltstone	Graywacke sandstone or siltstone
eous	large amount, unstable suite	Quartz-chlorite-pyribole graywacke sandstone or siltstone	Graywacke sandstone or siltstone
ally not distinguished from trix; if present, mainly cal- eous		Dolomite and calcite sandstones Foraminiferal sandstones and marls Gypsum sandstone Oolitic sandstones (See table 4)	

from micaceous quartzose sandstones, as well as other minor groups.

Claystones and siltstones.—Claystones and siltstones whose bedding or field aspects are those of shale are organized into appropriate groups in table 3. Siltstones classified in this table are distinct from those grouped with sandstones (table 2) as the former are primarily composed of particles which approach clay dimensions, whereas the latter are coarser in texture. Siltstones are, therefore, the connecting links between sandstones and shales, and the close association of these three textural groups enabled the writers to arrange shales into varieties paralleling those of sandstones. This permits a convenient connotation such as quartzose, subgraywacke, and graywacke shales.

The grain size limit of siltstone was selected as coarser than 1/100 mm. Ex-

TABLE 3.—*Claystones and siltstones*
(All claystones or siltstones which show bedding in thin units are called shales.)

Bulk Appearance		Hardness	Reaction to HCl	Disaggregated Residue	Disag
Texture	Color			Particle Size	Reco
Claystones predominate also silty claystone sandy claystone clayey siltstones Bedding blocky to fissile	light shades of green, gray, and blue predominate	soft, easily scratched, greasy or curdy powder	none to strong, generally slight or moderate	chiefly clay, silt variable	quartz, glau
					quartz, ofte
	shades of red and brown predominate				quartz, iron able
				clay	one
	dark shades of gray to black			chiefly clay, silt variable	quartz, pyri ous or humi
		generally moderately hard, "fluffy" powder			quartz, blac lain zeolite
Siltstones predominate also clayey siltstones sandy siltstones silty claystones Bedding, thin to less commonly blocky, fissile, fracture splintery or "pencil"	dark shades of gray and green	generally moderately hard, "flaky" powder		silt generally predominates over clay	quartz, mic
	dark shades of gray; red, brown, to black		none to slight	silt predominates over clay	mica promi minor, som ments comm
					mica promi iron oxide, amounts
					calcareous ca, feldspar
	dark shades predominate, commonly gray		slight to moderate		mica, quart
			none to slight		mica, felds
	dark shades of red, brown, variegated, also grays and greens	generally moderately hard, but also soft, granular powder	none to moderate	silt predominates over clay, sand grains common	quartz, mic
					quartz, mic gypsum, do
"Dense" rocks predominate, siltstones and claystones	dark shades predominate commonly gray; black	generally hard, scratched with difficulty	none to slight	silt predominates, sorting poor, sand grains common	chlorite, fe mica, glass,
Bedding blocky to splintery	white to light gray				glass shard ments

perience has shown that siltstones whose most abundant particles exceed this diameter show the field characteristics of sandstones; whereas finer sediments have the characteristics of typical shales.

The arrangement of table 3 is patterned after the other tables in that the rock is examined first on the basis of its most obvious characteristics and then is subdivided on the basis of more refined observations. The tests applied are all limited to simple ones which can be made under the binocular microscope, yet, despite the crude nature of some of these

TABLE 3.—*Claystones and siltstones*

(All claystones or siltstones which show bedding in thin units are called shales)

Disaggregated Residue Recognizable Minerals	Cement and other Features	Examples	Group Name
quartz, glauconite	cement poor, often calcareous, may contain calcareous pellets, "slip" fracture common	Glauconite-quartz claystone Glauconite-quartz siltstone Glauconite-quartz clayey siltstone	Quartzose shales
quartz, often in small amounts		Quartz claystone Quartz siltstone Quartz silty claystone etc. "Fireclay"	Quartzose shales
quartz, iron oxide, quantities variable		Iron oxide-quartz claystone Iron oxide-quartz siltstone "Red-bed" shales	Quartzose shales
stone	swells markedly when wet	Bentonite	?
quartz, pyrite common; carbonaceous or humic residue variable	cement poor to moderate, often calcareous, may contain calcareous pellets	Pyrite-quartz claystone, carbonaceous-quartz claystone etc.	Quartzose shales
quartz, black iron sulfide; may contain zeolites	cement moderate, often siliceous, may contain plankton, spores	Iron sulfide-quartz claystone Iron sulfide-quartz clay siltstone, etc.	Quartzose shales
quartz, mica, glauconite	cement moderate, generally slightly calcareous, also siliceous	Glauconite-mica clay siltstone etc.	Subgraywacke shales
mica prominent; quartz, feldspar minor, some pyribole; coal fragments common	cement moderate, siliceous to slightly calcareous	Quartz-mica siltstone Feldspar-mica clayey siltstone Carbonaceous-mica siltstone etc. "Underclay"	Subgraywacke shales
mica prominent; quartz, feldspar, iron oxide, and gypsum in variable amounts		"Red-bed" shales Iron oxide-mica siltstone Gypsum-mica siltstone etc.	Subgraywacke shales
calcareous matter prominent; mica, feldspar, quartz		Carbonaceous-mica siltstone etc.	Subgraywacke shales
mica, quartz, phosphates	cement moderate to good, generally calcareous	Phosphatic-mica siltstone Phosphatic, calcareous, mica siltstone etc.	Subgraywacke shales
mica, feldspar, glass	cement good, generally siliceous	Tuffaceous-mica siltstone etc.	Subgraywacke shales; grade into graywacke shales
quartz, mica, feldspar, iron oxide	cement poor to good; commonly calcareous; also siliceous	Arkosic siltstone Feldspathic siltstone Iron oxide feldspathic clay siltstone etc.	Arkosic shales
quartz, mica, feldspar, iron oxide, gypsum, dolomite, calcite		Gypsiferous arkosic siltstone Iron oxide, gypsiferous arkosic silty claystone etc.	Arkosic shales
chlorite, feldspar, quartz, chert, mica, glass, pyrite, rock fragments	cement good, generally siliceous, associated with graywackes	Chloritic siltstone Siliceous-chloritic clayey siltstone Pyrite-chlorite silty claystone Tuffaceous-chlorite siltstone Pyritic-carbonaceous siltstone	Graywacke shales; grade into subgraywacke shales
glass shards, or devitrified fragments		Porcellanite	Graywacke shales

tests, most shales can be grouped into their respective types. The writers anticipate that certain shales will prove troublesome to classify, and since no distinction is made as to the nature of the predominant minerals, it is to be expected that the classification of shales will be subject to modification as the chemistry and mineralogy of clay minerals is better understood. The objective of the present system is to establish a rapid means of classification.

The bulk appearance of shales is one of their most easily identified features. This

TABLE 4.—*Chemical rocks, mainly carbonates*

Bulk Textural Appearance	Particles or Crystals			Matrix[1]
	Size	Appearance	Composition	Appearance
Coarse to medium particles, crystals, or fragments in matrix	>¼ mm	tests or parts of tests of macroscopic organisms	calcareous, less commonly siliceous or pyritic	dense to coarsely crystalline
				irregularly distributed between organic structure; much open pore space
		particles and matrix similar	limestone, dolomite	dense to coarsely crystalline
			limestone, dolomite, chert, etc.	
		particles and matrix similar, flat pebbles	limestone or dolomite	dense to finely crystalline
		pisolitic or oolitic	calcite, dolomite, silica, siderite, hematite, phosphate, etc.	dense to finely crystalline, rarely coarse
		interlocking or cemented crystals	calcite or dolomite	dense to coarsely crystalline, difficult to distinguish
			gypsum, anhydrite, halite, etc.	
		nodules; dense, irregular	limestone, dolomite, siderite	dense to finely crystalline or chalky
Fine, particulate or fragmental in matrix	± ¼ mm	tests of microscopic organisms fragments of macroscopic organisms	calcite or dolomite; less commonly silica	dense to finely crystalline, commonly chalky
Dense to finely crystalline	<¼ mm	sub-vitreous or porcellaneous, with scattered crystals of organic remains	calcite or dolomite, rarely siderite, anhydrite, etc.	
		sub-vitreous to vitreous	silica	

[1] In f

includes the color, texture, and the fracture. Claystones, siltstones, and dense shales can thus be distinguished from one another. Once arranged in such categories the hardness and reaction to HCl become important tests in further subdivision. Hardness is determined by scratching with a needle and the degree of hardness as well as the nature of the resulting powder is normally important. Inasmuch as the shales associated with quartzose sandstones are prevailingly claystones, they are generally soft, and the powder is curdy or unctuous rather than granular or fibrous. Subgraywacke shales are on the whole more thoroughly cemented and contain more silt which produces a gritty and granular powder when scratched. Most shales will disaggregate either in HCl or concentrated NaOH after powdering in a mortar.[2] The powder is placed on two watch glasses and a few drops of the concentrated NaOH and dilute HCl added to the respective glasses. The composition of the residue and its dimensions can be determined readily by inspection. Certain important minerals such as clay, quartz, glauconite, mica, pyrite, feldspar, and gypsum can be identified in the residue and these are important in refining the classification of the shale.

Selecting names for the shales is difficult, but those which contain less than one per cent of mica and the residue consists almost entirely of quartz and clay minerals in any proportion are designated as quartzose shales. They are associated

[2] Krumbein (1947) has outlined a routine for examination of shales under the microscope.

TABLE 4.—*Chemical rocks, mainly carbonates*

Matrix[1] Composition	Other Features	Examples	Group Name
calcite or dolomite, rarely argillaceous	may have many structures of detrital rocks	Fusulinid limestone Coquina Crinoidal dolomite	Fossiliferous-fragmental
dolomite more common than calcite	poorly bedded, rubbly	Reef core dolomite	
dolomite or calcite; anhydrite; hydrocarbons	typical structures of detrital rocks	Dolomite "sand" Saccharoidal limestone	Fragmental
dolomite, calcite, anhydrite; red clay common	poorly sorted, angular fragments; massive; obscure bedding and lateral continuity	Solution breccia Collapse breccia	
calcite, dolomite, commonly argillaceous and glauconitic	shingled and edgewise pebbles commonly cross-bedded, ripple-marked, etc.	Edgewise conglomerate Flat-pebble conglomerate	
calcite, dolomite, silica, hematite, phosphate, clay	fossils aberrant; many structures of detrital rocks	Oolitic limestone Pisolitic phosphate rock	Oolites and pisolites
dolomite, calcite, anhydrite	may have fossils and primary structures obscured by re-crystallization	Saccharoidal dolomite Calcite "sand" Crystalline dolomite	Crystalline
gypsum, anhydrite, halite, etc.	white, pink, translucent, soft	Bedded anhydrite Bedded salt	Evaporite
limestone, dolomite, commonly argillaceous	conchoidal fracture or breaking along nodule contacts	Nodular limestone	Nodular
calcite, dolomite, silica; commonly argillaceous	well bedded to massive, well preserved organisms	Foraminiferal limestone Chalk, Diatomite	Normal marine
	scratched with steel; conchoidal fracture; often with blebs and mottling of different color and coarser texture	"Lithographic" limestone Dense dolomite Siliceous limestone	Dense
	scratches steel; conchoidal fracture; translucent; beds, nodules, lentils, etc.	Chert	Chert

[1] In finely crystalline rocks matrix and cement are usually indistinguishable; if present calcitic

with quartzose sandstones and are, therefore, recognized as a group. Such shales are distinguished by prefixing the words "quartz" or "clay" before the word "shale," "claystone," or "siltstone." Shales associated with subgraywacke sandstones are micaceous and, hence, are designated micaceous claystones or siltstones.

Shales associated with arkosic sandstones are called arkosic shales. They are characterized by the presence of feldspar in the disaggregated residue. Red, brown, and variegated colors prevail and gypsum is commonly present both in the residue and as thin stringers or intercalated beds.

Graywacke shales are recognized by the occurrence of chlorite in the disaggregated residue, their tendency toward dark shades, and their siliceous cement. In table 3 they are called chloritic shales to distinguish them from the other types in which chlorite is absent or a very minor constituent.

Chemical rocks.—Chemical rocks are arranged in table 4, which is constructed on the same plan as the others. The rock is first classified according to its bulk aspect, and refinement of the classification proceeds with inspection of the details of the rock. The allochthonous rocks are all detrital in their origin, but chemical rocks consist of both clastic and non-clastic varieties, and texture is of prime importance in distinguishing between the two major groups. This can be readily described as particulate (composed of particles, fragments, or crystals) or dense. Most autochthonous rocks can be placed by inspection into one or another of these

categories. Once this is done the character of the particles, fragments, or crystals, can be determined. Hence, the rock is further subdivided on the basis of the appearance of the particles, their composition, and their size. The matrix is then examined in terms of its appearance and its composition. Inasmuch as the matrix and the cement of dense chemical rocks are indistinguishable, the character of cement or matrix does not enter into the classification of these types.

CONCLUDING REMARKS

As far as possible the organization suggested by tables 1–4 is devoid of tectonic or environmental implications. However, review of the lithologic types which are classified into the several "group names" reveals the fact that these are natural associations of common tectonic habit. Such tectonic associations have been discussed previously by the writers (1948), but no exhaustive treatment of the numerous rock species and their interrelationships was attempted. In view of the larger number of individual rock types covered in the present paper, it is interesting to consider the position of these numerous species within the larger grouping. The following tectonic organization of the rocks included in the tables is presented as the writers' interpretation of the natural associations which these rocks exhibit. In contrast to the purely operational procedures involved in the organization of the tables, the following arrangement is interpretive.

In the following outline the rock species are lifted from their positions on the operational tables and rearranged according to tectonically controlled groupings.

By reference to the outline above, and

Stable Shelf Associations

Conglomerates
- A. Quartz pebble, chert pebble, quartzite pebble and other quartzose conglomerates.
- B. Iron oxide pebble, and other residual conglomerates
- C. Carbonate rock, edgewise, reef-flank etc.
- D. Others classified with uncertainty

Sandstones
- A. Quartzose sandstones
- B. Arkoses of the granite wash type

Shales
- A. Quartzose shales

Chemical Rocks
- A. Fossiliferous-fragmental limestones
- B. Fragmental limestones
- C. Oolitic and pisolitic limestones
- D. Crystalline limestones
- E. Normal marine limestones
- F. Dense limestones

} and dolomitized equivalents

- G. Evaporites
- H. Chert

Unstable Shelf Associations

Conglomerates
- A. Quartz pebble, chert pebble, quartzite pebble and other quartzose conglomerates.
- B. Iron oxide pebble, and other residual conglomerates
- C. Carbonate rock, edgewise, reef-flank etc.
- D. Others classified with uncertainty

Sandstones
- A. Quartzose sandstones
- B. Arkoses of the granite wash type
- C. Quartz-mica, and carbonaceous subgraywackes

Shales
- A. Quartzose shales
- B. Subgraywacke shales

Chemical Rocks
- A. Fossiliferous-fragmental limestones
- B. Fragmental limestones
- C. Oolitic and pisolitic limestones
- D. Crystalline limestones
- E. Normal marine limestones
- F. Dense limestones

} and dolomitized equivalents

- G. Nodular limestones
- H. Chert
- I. Evaporites

Intracratonic Basin Associations

Conglomerates
- A. Quartz pebble, chert pebble, quartzite pebble and other quartzose conglomerates.
- B. Iron oxide pebble, and other residual conglomerates
- C. Carbonate rock, edgewise, reef-flank etc.
- D. Others classified with uncertainty

Sandstones
- A. Quartzose sandstones
- B. Arkoses of the granite wash type
- C. Quartz-mica, and carbonaceous subgraywackes
- D. Subgraywackes
- E. Basin arkoses

Shales
- A. Quartzose shales
- B. Subgraywacke shales
- C. Arkosic shales

Chemical Rocks
- A. Fossiliferous-fragmental limestones
- B. Fragmental limestones
- C. Oolitic and pisolitic limestones
- D. Crystalline limestones
- E. Normal marine limestones
- F. Dense limestones

} and dolomitized equivalents

- G. Nodular limestones
- H. Chert
- I. Evaporites
- J. Primary dolomites

Geosynclinal Associations

Conglomerates
- A. Agglomerates
- B. Graywacke conglomerates

Sandstones
- A. Graywackes

Shales
- A. Graywacke shales

Chemical Rocks
- A. Dense siliceous limestones
- B. Bedded cherts

with some knowledge of the distribution, rate of change of thickness, and shape of the unit, the strata of any stratigraphic unit investigated at any point of observation may be classified according to the degree of tectonism in effect during deposition. Thus, a rock unit like the Tensleep sandstone (Pennsylvanian) of Wyoming is composed of quartzose sandstones with minor fragmental limestones and has a relatively even thickness over a wide area. Therefore this unit is readily classified as a product of stable shelf deposition. Other rock or time-rock units may exhibit vertically successive variations in the degree of tectonism expressed. Such complex units may be differentiated into vertically successive subdivisions according to the tectonic habit indicated by the associated lithologies.

The writers (1949) have previously discussed the tectonic differentiation of a stratigraphic unit and have applied the term "tectotope" to groupings of strata so defined. It is clear that the recognition of individual tectotopes, the determination of over-all tectonic aspect of a stratigraphic unit, and analysis of lateral variations in tectonic aspect, should follow as interpretive steps after the sediments involved have been objectively classified according to their observable attributes.

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FIGS. 1–2, APRIL, 1950

THE PETROLOGY OF SOME DES MOINES SERIES SANDSTONES OF IOWA

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Lake Charles, Louisiana

ABSTRACT

Mineral and textural analyses reveal that the basal sandy units of the simple cyclothems of the Pennsylvanian Des Moines series of south central Iowa are well sorted, fine grained to silty, quartzose sandstones. Though always well sorted, the samples from channel facies developments are distinctly more coarse than those from sheet facies developments. Mineralogically the sandstones are composed of stable species derived largely from pre-existing sediments but containing some apparently fresh material from granitic and metamorphic terranes. The light minerals are quartz, orthoclase, plagioclase, muscovite, biotite, and chlorite. Abundant heavy minerals are zircon, garnet, tourmaline, and leucoxene; chloritoid, barite, apatite, staurolite, rutile, anatase, magnetite, hematite, and pyrite also occur. Conditions of deposition, possible provenance areas, and variations in mineral occurrence and abundance are discussed.

INTRODUCTION

The Pennsylvanian Des Moines series of Iowa contains a number of simple cyclothems, most of which contain a basal sandstone member. Each sandstone member consists of a sheet facies and a channel facies, the former being the more widespread. The objectives of this investigation were to study the mineralogy and textures of several of these sandstones through a considerable vertical range to determine whether there are critical differences, (1) between the facies of any one sandstone, (2) between the several sandstones, and (3) to search for information concerning provenance areas. Samples were collected from the following cyclothems which are listed in order from oldest to youngest: Munterville, Abingdon, Ardmore, Wheeler, Bedford, Blackjack Creek, Higginsville, Marshall, Myrick Station, Coal City, and Worland. In addition, one sample of an unidentified sandstone in the Missouri series was collected. The minerals were identified; frequency counts of both heavy and light mineral fractions were made; the samples were sieved according to standard methods; and the results were tabulated.

ACKNOWLEDGEMENTS

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LITHOLOGY

Field descriptions of these sandstones or their nearby equivalents were given by Cline (1941) and Wanless (1930), and their lithology in Iowa and surrounding states is well known. Sandstones in the Des Moines series of Iowa typically are gray, yellow, buff, or brown, moderately friable (although locally well cemented), fine-grained, micaceous, and occur in relatively thin sheets (two to ten feet) of rather wide areal extent. They are subject to both vertical and lateral variations in texture, and change from platy to massive bedding. They may be divided into two facies: (1) the sheet or blanket facies is more or less uniform in thickness and

commonly rests with apparent conformity on the underlying strata; (2) the channel facies is relatively local but occurs wherever Pennsylvanian cyclothems are found. Varying rapidly in thickness, they rest unconformably upon the underlying strata and may cut through scores of feet of older strata. Basal conglomerates of locally derived material are not uncommon.

TECHNIQUES

Sampling

With the one exception mentioned in the introduction, only outcrops of known identity were sampled. As channel sampling proved impractical, representative chip samples, as suggested by Twenhofel and Tyler (1941, p. 21), were collected, care being taken to dig well into the outcrop to insure the getting of unweathered material. Whether the outcrop represented the sheet facies or the channel facies was noted.

Heavy Mineral Separation

In disaggregation, the more friable samples were crumbled by hand, the firmly cemented samples were jaw crushed into fragments with diameters of one or two centimeters and these fragments were passed through a disc pulverizer set so coarsely that the sand came through as small clusters of grains. A Jones sample splitter was used to obtain a split of about fifty grams. The split portion was then treated for about two hours with a four to one solution of tepid hydrochloric acid. That this treatment destroyed apatite and perhaps other minerals is recognized, but the stong cementation (usually calcium carbonate or iron oxide) of some samples necessitated its use. After being washed and dried, the remaining small clusters of grains were gently rubbed with the fingers to complete disaggregation. Separation of the heavy minerals was accomplished by centrifuging, using acetylene tetrabromethane of specific gravity 2.91. The residue was split with an Otto Microsplit, a portion was mounted in balsam, and the remainder saved for immersion work and reference.

Identification and Counting

Identification of the suite was effected with the petrographic microscope using permanent balsam mounts and temporary mounts in immersion liquids. The universal stage was used in confirmation. Random fields were used in making percentage counts. Of the heavy minerals two counts were made: one, a 300 grain unrestricted count of all grains (table 1); another, a 300 grain count exclusive of opaques and titanium minerals (table 2). This second count was necessitated because of the extreme abundance of opaque grains, mostly leucoxene. A microsplit portion of the light fraction was mounted in an immersion liquid of refractive index 1.545 for counting. Only 100 grains per samples were counted. Inclusions in the quartz were classified according to a system set up by Mackie (1896) and followed by Gilligan (1919) and Tyler (1936). Muscovite and chlorite, though present in the heavy fractions, largely remained with the lights and were arbitrarily so included.

Mechanical Analyses

To a representative split of the original sample, concentrated hydrochloric acid was added in quantity and the sample heated for about twenty-four hours. This rather drastic treatment was necessary to thoroughly disaggregate the samples. The small clusters that remained after washing and drying were gently rubbed with the fingers to effect complete disaggregation, but even so, it is recognized that a few small clusters remained in all size grades. Each sample was weighed on a triple beam balance, and then sieved for fifteen minutes in a Ro-Tap using screens of the following diameters: 0.061 mm, 0.088 mm, 0.124 mm, 0.175 mm, 0.246 mm. The bottom pan caught material of silt and clay sizes. The sieve fractions were weighed and tabulated (tables 3, 4, and 5).

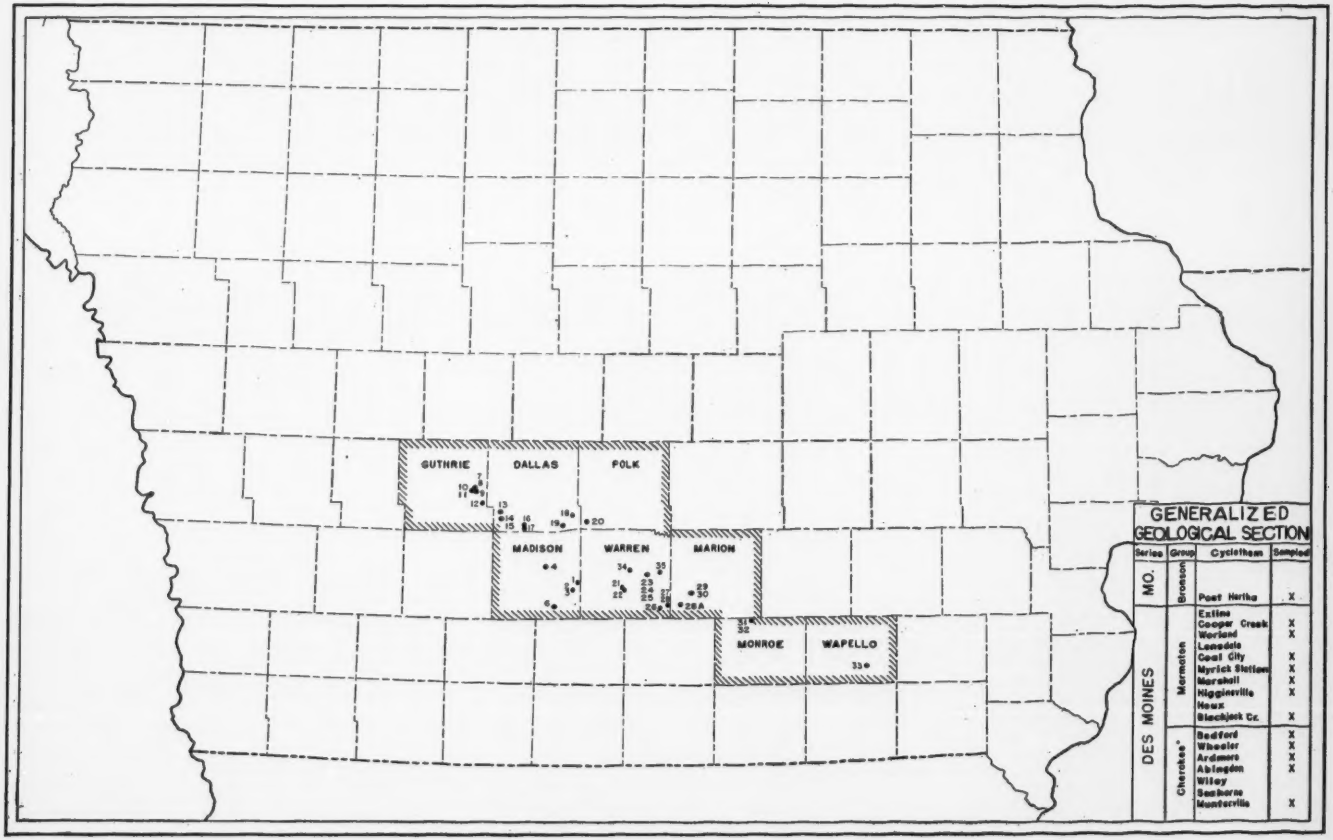

FIG. 1.—Index Map Showing Sampled Localities.

MINERALOGY

Heavy Minerals

Zircon.—Zircon, the most abundant non-opaque mineral, occurs as slender, water clear, perfect prisms with pyramidal terminations, as short stumpy clear crystals, and as intensely zoned crystals. It is present with or without inclusions. The clear zircons usually display few signs of abrasion or weathering. The mineral also is commonly found in good crystal form in grains which range in color from a nearly opaque brown through straw colors to the clear specimens. These colored zircons vary from dirty, brownish-yellow, pitted, well-rounded grains to clear, unaltered crystals. Inclusions characteristically are well formed crystals of apatite, zircon, tourmaline, and rutile, but inclusions of irregular form are present. They also occur in quantity without orientation although in some grains straw-colored, dusty zircons form the core of larger, clear crystals. Gradational differences in birefringence make varietal differentiation on this basis difficult. The variety of form, color, zoning, and degree of weathering is literally endless, but for counting purposes three varieties are distinguished. (1) Normal zircons, showing approximately normal refringence and birefringence, range in color from brown through straw to clear. (2) Hyacinth zircons, having a pale violet-pink color and very high refringence and birefringence, are rather rare and usually are well rounded and worn. (3) Malacon, distinguished by its low birefringence, is rare. A complete range in birefringence from first order colors upward makes the malacon difficult to count and subject to considerable personal error.

Garnet.—Garnet occurs as irregular fragments which usually exhibit a characteristic checked etch pattern. Inclusions occur but are not prominent. For counting purposes three varieties are distinguished. (1) Clear, colorless garnet is the most abundant. The checked etch pattern is very distinct. A few grains have abundant fine inclusions so that the mineral has a dusty appearance. (2) Pink, or rose-colored garnet is next in abundance. There are many rounded frosted grains, and the etch patterns are not so common as in the clear variety. (3) A less common type, which may not rate varietal rank is similar to the clear type but has a pale yellow color. Precise distinction between the two is difficult.

Tourmaline.—Tourmaline occurs most frequently as euhedral prisms but also occurs as rounded grains and as jagged and irregular fragments. Typically the tourmaline is fresh and relatively free from abrasive effects and alteration, but some is fractured, ragged in appearance, and shows evidence of alteration. Inclusions, which are abundant, commonly are concentrated along the vertical axis of the crystal. Striations parallel to the C axis are common. For counting purposes, the tourmaline is separated into four varieties on the basis of color and pleochroism. (1) One type is brown or pleochroic from colorless to brown. Some grains are brown on one end, blue on the other, and have sharp color boundaries. The brown variety has relatively few, mostly clear and formless inclusions. It usually occurs as irregular fragments and rounded grains. (2) A second type is clear to cloudy-violet, light green or blue, changing to cloudy-blue and even opaqueness upon rotation. This variety has the best crystal development as well as the greatest number and diversity of inclusions, although many specimens are completely free from inclusions. (3) Green-black, nearly opaque, worn grains of tourmaline occur infrequently and may not deserve varietal rank. (4) Brilliant sky-blue, or marine-blue tourmaline, exhibiting only slight pleochroism occurs sparsely and may not be of varietal rank.

Chloritoid.—Chloritoid is present as olive-green, green-blue, and blue flakes which show distinct basal cleavage. The grain outline is usually roughly oval but may be ragged as determined by cleavages. Typically the flakes are shot through with opaque, blotchy inclusions

TABLE 1.—*Heavy Mineral Frequency Count*
(unrestricted, 300 grains per sample)

Formation	Sample No.	Zircon (total)	Normal	Hyacinth	Malacon	Garnet (total)	Clear	Pink	Yellow	Tourmaline (total)	Brown	Smoky-grn. & blue	Green-Black	Blue	Chloritoid	Barite	Staurolite	Leucoxene	Anatase	Rutile (total)	Yellow	Red-brown	Magnetite	Hematite	Pyrite
Post Hertha	5	18.3	18.3	0.0	0.0	7.7	7.3	0.0	0.4	5.7	0.7	4.0	1.0	0.0	0.0	0.0	0.0	53.7	0.0	1.3	1.0	0.3	13.3	0.0	0.0
Cooper Ck.	4	23.0	23.0	0.0	0.0	5.0	4.3	0.0	0.7	4.7	2.0	2.3	0.0	0.4	0.0	0.0	0.0	34.0	0.0	4.3	2.0	2.3	29.0	0.0	0.0
Worland	3	22.3	21.7	0.7	0.0	8.7	7.0	0.3	1.4	8.7	4.3	4.4	0.0	0.0	0.0	0.7	0.7	41.9	0.0	2.0	1.7	0.3	15.0	0.0	0.0
Do.	6	29.3	29.3	0.0	0.0	7.3	6.0	0.0	1.3	7.7	4.0	3.3	0.0	0.4	0.0	0.0	0.0	48.1	0.0	1.3	1.0	0.3	6.3	0.0	0.0
Do.	16	37.3	37.0	0.3	0.0	10.0	8.7	1.0	0.3	4.3	2.0	2.0	0.3	0.0	0.0	0.0	0.0	42.8	1.0	4.3	2.0	2.3	0.3	0.0	0.0
Do.	17	36.3	36.3	0.0	0.0	7.7	7.0	0.0	0.7	1.4	0.7	0.7	0.0	0.0	0.0	0.0	0.0	42.0	0.0	3.6	2.3	1.3	9.0	0.0	0.0
Coal City	2	26.7	26.7	0.0	0.0	4.0	3.7	0.0	0.3	5.0	1.0	3.7	0.3	0.0	0.3	9.3	0.0	37.4	0.0	1.3	1.3	0.0	6.7	2.3	7.0
Myrick Stn.	7	20.3	20.3	0.0	0.0	13.0	13.0	0.0	0.0	4.0	1.7	2.0	0.3	0.0	0.0	0.0	0.0	47.3	0.0	5.0	2.0	3.0	6.0	2.7	1.7
Do.	12	29.0	28.3	0.7	0.0	17.0	15.3	0.7	1.0	9.6	2.3	6.0	1.3	0.0	0.0	0.0	0.7	29.3	7.7	6.7	3.7	3.0	0.0	0.0	0.0
Do.	18	32.3	32.3	0.0	0.0	19.0	18.0	0.0	1.0	3.0	1.0	6.0	0.3	0.7	0.0	0.0	0.0	29.6	0.0	7.4	3.7	3.7	3.7	0.0	0.0
Higginsville	22	21.0	21.0	0.0	0.0	8.3	8.0	0.0	0.3	10.6	3.3	7.0	0.0	0.3	2.3	0.7	0.0	55.4	0.0	1.7	1.7	0.0	0.0	0.0	0.0
Blackjack Ck.	9	22.4	21.7	0.7	0.0	11.1	9.7	0.7	0.7	4.4	2.0	1.7	0.7	0.0	1.7	0.0	0.0	52.0	1.7	5.0	2.0	3.0	1.7	0.0	0.0
Do.	11	20.7	20.7	0.0	0.0	7.4	6.7	0.7	0.0	4.0	1.0	3.0	0.0	0.0	5.3	0.0	0.0	28.2	31.7	2.7	1.7	1.0	0.0	0.0	0.0
Do.	19	23.7	23.7	0.0	0.0	2.7	2.0	0.0	0.7	7.7	1.7	6.0	0.0	0.0	0.0	15.0	0.0	43.3	0.0	6.3	3.0	3.3	0.3	0.7	0.3
Do.	21	45.3	45.0	0.3	0.0	4.0	3.7	0.0	0.3	6.0	2.0	3.3	0.7	0.0	3.7	0.0	0.0	37.4	0.3	3.3	2.3	1.0	0.0	0.0	0.0
Do.	23	30.0	30.0	0.0	0.0	2.0	1.3	0.0	0.7	1.7	0.7	1.0	0.0	0.0	0.0	5.0	0.0	30.3	0.0	2.3	2.3	0.0	0.0	28.7	0.0
Do.	24	41.3	41.3	0.0	0.0	5.0	4.7	0.3	0.0	6.7	1.7	5.0	0.0	0.0	2.0	8.3	0.0	32.7	0.7	3.3	3.3	0.0	0.0	0.0	0.0
Do.	26	19.6	19.3	0.0	0.3	3.0	2.7	0.3	0.0	4.7	1.7	1.0	1.0	1.0	1.7	0.0	0.3	57.7	11.7	1.3	0.3	1.0	0.0	0.0	0.0
Do.	32	7.0	6.3	0.0	0.7	4.0	3.3	0.7	0.0	4.0	2.7	1.3	0.0	0.0	0.7	0.0	0.0	73.0	10.3	1.0	0.3	0.7	0.0	0.0	0.0
Do.	35	31.0	31.0	0.0	0.0	3.3	3.0	0.3	0.0	4.3	1.7	2.0	0.3	0.3	0.7	0.0	0.0	54.0	0.0	5.7	2.7	3.0	0.0	0.0	0.7
Bedford	10	46.0	46.0	0.0	0.0	4.7	0.0	0.0	0.0	6.6	1.0	5.0	0.3	0.3	0.7	0.0	0.0	38.4	0.3	3.0	0.7	2.3	0.3	0.0	0.0
Do.	25	30.3	30.3	0.0	0.0	2.7	2.7	0.0	0.0	5.0	1.7	3.0	0.3	0.0	2.7	0.7	0.0	54.9	2.0	2.4	1.7	0.7	0.0	0.0	0.0
Wheeler	15	42.0	42.0	0.0	0.0	3.7	2.7	0.0	0.7	2.8	1.0	1.8	0.0	0.0	0.0	0.0	0.0	38.5	1.0	2.8	1.6	1.2	8.0	1.2	0.0
Do.	20	9.0	9.0	0.0	0.0	0.7	0.7	0.0	0.0	0.7	0.0	0.7	0.0	0.0	0.0	75.7	0.0	11.3	0.3	2.3	1.3	1.0	0.0	0.0	0.0
Do.	34	37.7	37.0	0.7	0.0	0.7	0.7	0.0	0.0	2.3	0.3	1.3	0.7	0.0	0.0	31.0	0.0	25.4	0.3	2.3	0.7	1.6	0.3	0.0	0.0
Ardmore	31	2.3	2.3	0.0	0.0	2.3	2.3	0.0	0.0	0.6	0.3	0.0	0.3	0.0	0.0	0.0	0.0	27.5	1.3	0.3	0.0	0.3	0.0	0.0	65.7
Abingdon	27	13.0	12.8	0.2	0.0	15.3	15.3	0.0	0.0	11.8	5.0	5.8	1.0	0.0	4.0	2.5	0.7	49.9	0.0	2.8	2.0	0.8	0.0	0.0	0.0
Do.	28A	22.0	22.0	0.0	0.0	3.6	2.3	0.0	1.3	3.3	0.0	3.3	0.0	0.0	0.0	33.0	0.0	21.1	0.0	3.7	1.7	2.0	13.3	0.0	0.0
Munterville	13	23.6	23.3	0.3	0.0	5.6	4.3	1.3	0.0	7.3	1.3	5.0	0.7	0.3	0.0	0.0	0.0	58.1	3.0	2.1	0.0	2.1	0.3	0.0	0.0
Do.	28	33.6	33.3	0.3	0.0	0.0	0.0	0.0	0.0	10.0	6.7	1.7	0.3	1.3	0.0	0.0	0.0	54.8	0.0	1.6	0.3	1.3	0.0	0.0	0.0
Do.	30	40.0	40.0	0.0	0.0	2.7	2.7	0.0	0.0	5.6	1.7	3.3	0.3	0.3	0.0	0.0	0.0	49.4	0.0	2.3	2.0	0.3	0.0	0.0	0.0
Do.	33	4.3	3.3	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.1	43.6	0.0	0.0	0.0	0.0	0.0	0.0

which are commonly arranged in swirls and swarms. Some grains are slightly pleochroic in olive-green and blue.

Barite.—Barite occurs sporadically in the samples, but, where found, is usually in quantity. It is clear to faintly yellow in color and is present as highly irregular fragments and cleavage pieces. The several cleavages cause the barite to present confusing and apparently contradictory optical data. Determination is based on indices of refraction obtained by immersion methods and optic angle measurements with the universal stage. Pits and formless inclusions are abundant. In some samples barite has a pink color believed to be iron oxide.

Apatite.—Apatite is present but does not enter into the statistical count because it was largely destroyed by hydrochloric acid in disaggregating the samples. In check samples disaggregated without hydrochloric acid, apatite is present in small quantity as clear, ovoid grains characterized by elongate, clear inclusions oriented parallel to the principal crystallographic axis.

Staurolite.—Staurolite is rare but persistent. It is present as pale amber and straw-colored grains with sawtooth edges. The grains are slightly pleochroic in yellows. Minute inclusions are present in some cases.

Rutile.—Rutile is found in two major types differentiated largely by color. One variety typically is well developed as brilliant amber, elongate, prismatic grains, often diagonally striated and not uncommonly occurring as geniculate twins. Some crystals are quite fresh; others are rounded and worn. The second variety is red-brown (presumably the fox-red of other workers), may be stubby or elongate, and is in general more worn than the yellow variety. Striated grains and geniculate twins also occur in this variety. Many of the rutile grains approach opaqueness because of a coating of leucoxene. The writer believes that most of the red-brown grains are detrital whereas the amber variety is largely authigenic. Brookite possibly is present, but if present was counted as rutile.

Anatase.—Anatase is differentiated from rutile on the basis of its bright yellow color, its markedly euhedral crystals, and the optic sign. Beveled forms and geometrical patterns such as those described by Brammal (1929) are common. Because of its strikingly euhedral crystals most of it is thought to be authigenic. Some anatase is clouded with leucoxene to the point of becoming opaque and was undoubtedly counted as leucoxene.

Leucoxene.—Leucoxene competes with zircon in abundance. In reflected light it appears as white, creamy, tan, or pink, porcellanous material, irregular in shape, but also reflecting the crystal form of an earlier mineral. Dark brown grains of rutile, anatase, and perhaps other similar minerals were arbitrarily counted as leucoxene. Much of the leucoxene is undoubtedly derived from ilmenite, although on only a few grains could the ilmenite be seen showing through the leucoxene. Much of the leucoxene is magnetic, which points to ilmenite as a source.

Magnetite.—Magnetite is present in a few samples as opaque, highly magnetic grains that are a metallic black or steel gray in reflected light.

Hematite.—Hematite occurs sparingly. In reflected light it appears as red, irregular grains. It is thought to be authigenic, some being pseudomorphic after pyrite.

Pyrite.—Pyrite is present in several samples as tarnished yellow, jagged, formless aggregates and, occasionally, as well developed crystals. It may occur in such abundance as to mask out the other heavy minerals. It is considered authigenic.

Light Minerals

Quartz.—Quartz characteristically occurs as angular grains and subangular grains with fair sphericity, although no shape determinations were made. Many grains show secondary enlargement, whereas others appear to be outgrowths on grains of other minerals. Essentially

TABLE 2.—*Heavy mineral frequency count*
(exclusive of opaques and TiO_2 minerals, 300 grains per sample)

Formation	Sample No.	Zircon (total)	Normal	Hyacinth	Malacon	Garnet (total)	Clear	Pink	Yellow	Tourmaline (total)	Brown	Smoky grn. & blue	Green-black	Blue	Chloritoid	Barite	Staurolite
Post Hertha	5	56.7	56.7	0.0	0.0	23.7	23.0	0.0	0.7	19.3	4.7	13.1	1.3	0.0	0.3	0.0	0.0
Cooper Ck.	4	76.7	76.7	0.0	0.0	14.3	13.3	0.0	1.0	9.0	2.0	6.4	0.3	0.3	0.0	0.0	0.0
Worland	3	53.7	51.7	2.0	0.0	22.0	19.4	0.3	2.3	23.0	9.7	13.0	0.0	0.3	0.0	0.3	1.0
Do.	6	72.7	72.4	0.0	0.3	15.0	13.3	0.0	1.7	12.3	6.0	6.0	0.0	0.3	0.0	0.0	0.0
Do.	16	67.6	67.3	0.3	0.0	21.7	19.7	1.0	1.0	10.7	2.7	7.7	0.3	0.0	0.0	0.0	0.0
Do.	17	81.4	81.4	0.0	0.0	13.0	12.0	0.0	1.0	5.3	1.3	4.0	0.0	0.0	0.0	0.3	0.0
Coal City	2	66.4	65.8	0.3	0.3	6.0	5.0	0.0	1.0	9.3	1.7	7.0	0.3	0.3	0.3	18.0	0.0
Myrick Station	7	56.7	56.7	0.0	0.0	34.3	30.3	0.0	4.0	9.0	3.0	5.0	0.3	0.7	0.0	0.0	0.0
Do.	12	53.0	52.0	1.0	0.0	31.0	27.7	2.0	1.3	13.7	3.7	7.7	2.3	0.0	0.0	0.0	2.3
Do.	18	53.7	53.7	0.0	0.0	33.0	29.7	0.0	3.3	13.0	1.7	10.3	0.3	0.7	0.0	0.0	0.3
Higginsville	22	45.5	45.5	0.0	0.0	21.7	21.4	0.0	0.3	26.1	4.7	20.7	0.0	0.7	6.7	0.0	0.0
Blackjack Ck.	9	69.3	68.6	0.7	0.0	18.3	15.3	2.0	1.0	9.0	3.3	3.7	2.0	0.0	2.7	0.0	0.7
Do.	11	56.0	55.4	0.3	0.3	21.0	19.0	2.0	0.0	10.0	2.7	7.3	0.0	0.0	0.0	0.0	13.0
Do.	19	49.0	48.7	0.0	0.3	7.3	5.3	0.0	2.0	13.7	2.4	11.0	0.3	0.0	0.3	29.7	0.0
Do.	21	81.7	80.7	1.0	0.0	6.0	5.7	0.0	0.3	8.3	2.7	4.6	1.0	0.0	4.0	0.0	0.0
Do.	23	64.1	64.1	0.0	0.0	4.6	3.3	0.0	1.3	4.0	1.3	2.7	0.0	0.0	0.0	27.3	0.0
Do.	24	62.0	62.0	0.0	0.0	9.3	9.0	0.3	0.0	11.0	2.3	8.7	0.0	0.0	3.0	14.7	0.0
Do.	26	68.0	66.7	1.0	0.3	11.7	9.7	2.0	0.0	17.0	6.7	7.3	2.7	0.3	3.0	0.0	0.3
Do.	32	48.4	45.4	2.5	0.5	18.7	16.2	2.5	0.0	29.7	18.0	10.3	0.7	0.7	3.2	0.0	0.0
Do.	35	79.3	78.3	1.0	0.0	8.7	8.0	0.7	0.0	10.3	2.7	5.3	2.0	0.3	0.7	1.0	0.0
Bedford	10	75.3	75.3	0.0	0.0	6.7	6.7	0.0	0.0	16.7	2.7	13.4	0.3	0.3	1.3	0.0	0.0
Do.	25	71.7	71.7	0.0	0.0	8.0	8.0	0.0	0.0	13.0	4.0	8.0	0.7	0.3	5.0	2.3	0.0
Wheeler	15	74.3	74.3	0.0	0.0	7.0	6.1	0.3	0.6	5.3	1.2	4.1	0.0	0.0	0.7	12.7	0.0
Do.	20	12.0	11.7	0.0	0.3	0.7	0.7	0.0	0.0	1.0	0.3	0.7	0.0	0.0	0.0	86.3	0.0
Do.	34	46.7	46.0	0.7	0.0	2.0	1.7	0.0	0.3	3.0	0.3	1.7	1.0	0.0	0.0	48.3	0.0
Ardmore	31	35.9	33.6	2.0	0.3	41.7	38.0	3.7	0.0	17.7	11.4	4.3	1.3	0.7	3.0	1.3	0.7
Abingdon	27	31.9	30.9	1.0	0.0	30.5	28.8	1.7	0.0	21.7	9.0	10.7	2.0	0.0	9.5	5.4	1.0
Do.	28A	34.6	34.6	0.0	0.0	5.7	4.4	0.0	1.3	8.0	0.7	7.3	0.0	0.0	0.0	51.7	0.0
Munterville	13	67.4	66.1	1.3	0.0	15.0	12.7	2.0	0.3	17.0	4.0	11.0	0.7	1.3	0.3	0.3	0.0
Do.	28	66.3	65.3	1.0	0.0	0.7	0.0	0.0	0.7	33.0	15.0	11.7	3.3	3.0	0.0	0.0	0.0
Do.	30	82.6	81.9	0.0	0.7	3.7	3.7	0.0	0.0	13.0	4.0	7.3	0.7	1.0	0.0	0.7	0.0
Do.	33	82.3	82.3	0.0	0.0	5.7	4.4	1.3	0.0	11.3	5.3	4.3	1.7	0.0	0.7	0.0	0.0

TABLE 3.—*Light mineral frequency count*
(100 grains per sample)

Formation	Sample No.	Quartz (total)	with acicular inclusions	with regular inclusions	with irregular inclusions	Orthoclase	Plagioclase	Mica	Chloritic Material
Post Hertha	5	93.0	3.0	0.0	90.0	5.0	0.0	0.0	2.0
Cooper Ck.	4	87.0	1.0	1.0	85.0	4.0	0.0	2.0	7.0
Worland	3	79.0	3.0	4.0	72.0	5.0	0.0	9.0	7.0
Do.	6	86.0	2.0	1.0	83.0	6.0	0.0	2.0	6.0
Do.	16	86.0	0.0	0.0	86.0	9.0	0.0	3.0	1.0
Do.	17	93.0	6.0	7.0	80.0	5.0	0.0	1.0	1.0
Coal City	2	84.0	1.0	2.0	81.0	2.0	1.0	3.0	10.0
Myrick Stn.	7	83.0	0.0	3.0	80.0	8.0	0.0	3.0	4.0
Do.	12	94.0	1.0	0.0	93.0	4.0	1.0	0.0	1.0
Do.	18	95.0	4.0	3.0	88.0	4.0	0.0	0.0	1.0
Marshall	8	92.0	3.0	0.0	89.0	4.0	0.0	2.0	2.0
Higginsville	22	83.0	3.0	3.0	77.0	8.0	1.0	5.0	3.0
Blackjack Ck.	9	84.0	0.0	0.0	84.0	5.0	0.0	5.0	6.0
Do.	11	86.0	3.0	0.0	83.0	4.0	0.0	4.0	6.0
Do.	19	91.0	2.0	0.0	89.0	4.0	0.0	4.0	1.0
Do.	21	84.0	4.0	0.0	80.0	4.0	2.0	5.0	5.0
Do.	23	Too fine to make a reliable count							
Do.	24	86.0	2.0	0.0	84.0	5.0	1.0	7.0	1.0
Do.	26	86.0	1.0	0.0	80.0	5.0	0.0	3.0	16.0
Do.	32	77.0	5.0	6.0	66.0	12.0	1.0	5.0	3.0
Do.	35	86.0	1.0	1.0	84.0	6.0	0.0	1.0	7.0
Do.	1	90.0	2.0	1.0	87.0	2.0	0.0	4.0	3.0
Bedford	10	85.0	1.0	0.0	84.0	5.0	0.0	1.0	9.0
Do.	25	83.0	3.0	1.0	79.0	5.0	0.0	8.0	4.0
Do.	26	81.0	1.0	0.0	80.0	5.0	0.0	3.0	11.0
Wheeler	15	92.0	0.0	0.0	92.0	5.0	0.0	1.0	2.0
Do.	20	88.0	2.0	0.0	86.0	4.0	0.0	4.0	4.0
Do.	34	90.0	0.0	2.0	88.0	6.0	0.0	1.0	3.0
Ardmore	31	75.0	4.0	9.0	62.0	13.0	4.0	7.0	1.0
Abingdon	27	80.0	2.0	1.0	77.0	3.0	0.0	5.0	12.0
Do.	28A	85.0	4.0	0.0	81.0	2.0	0.0	5.0	8.0
Munterville	13	83.0	1.0	1.0	81.0	14.0	1.0	1.0	1.0
Do.	28	86.0	5.0	1.0	80.0	2.0	1.0	3.0	8.0
Do.	30	90.0	6.0	6.0	78.0	3.0	0.0	5.0	2.0
Do.	33	85.0	2.0	1.0	82.0	11.0	0.0	1.0	4.0
Do.	29	Too fine to make a reliable count							

all the grains have formless, liquid, gaseous, or solid inclusions, which are clear or opaque. Chert occurs sparingly as finely crystalline quartz aggregates.

Orthoclase.—Orthoclase, occurring as cleavage fragments and rounded grains, is identified by its refractive index and the presence of such alteration products as kaolinite, and, more rarely, sericite. Microcline, counted as orthoclase, is identified by its grid twinning. Some grains, showing little or no alteration effects, are thought to be authigenic feldspar, but classification as such is not conclusive.

Plagioclase.—Plagioclase of high albite content is determined on the basis of index of refraction and twinning. It characteristically exhibits extensive alteration to kaolinitic materials.

Muscovite.—Muscovite is found in relatively large flakes of standard ap-

TABLE 4.—*Results of mechanical analyses in percent weights by sieve sizes*

Sample No.	Size of opening in millimeters					
	0.246	0.175	0.124	0.088	0.061	pan
1	0.0	0.1	1.3	11.7	31.3	55.6
2	0.3	2.9	6.1	11.4	23.4	55.9
3	0.6	5.4	16.0	31.7	17.7	28.6
4	1.2	3.9	14.3	22.2	25.6	32.8
5	0.7	3.0	12.5	22.1	41.3	20.4
6	0.1	0.3	1.4	7.3	24.9	66.0
7	—	—	—	—	—	90.0+
8	—	—	—	—	—	90.0+
9	1.3	11.6	28.4	24.5	14.9	19.3
10	0.5	2.8	15.0	39.8	25.0	16.9
11	0.9	13.7	33.8	27.3	10.7	13.6
12	4.1	20.5	27.5	27.0	10.3	10.6
13	16.1	35.7	23.5	10.1	4.2	10.4
14	No analysis					
15	0.2	1.5	12.8	24.9	22.3	38.3
16	1.0	10.4	24.7	25.3	14.3	24.3
17	0.4	0.8	2.3	8.6	12.4	75.5
18	15.0	23.3	24.9	15.4	11.9	9.5
19	No analysis					
20	0.4	1.1	7.0	14.3	18.0	59.2
21	1.2	3.5	19.1	36.6	22.5	17.1
22	0.3	1.2	6.0	28.0	31.8	32.7
23	0.5	0.7	3.0	7.5	8.2	80.1
24	0.8	4.8	13.2	19.7	22.9	38.6
25	1.4	4.7	11.8	23.5	23.4	35.2
26	15.8	28.0	25.9	9.6	4.6	16.1
27	2.4	12.7	37.6	24.4	8.7	14.2
28	0.4	7.1	9.3	12.2	19.8	51.2
28A	0.1	6.0	12.7	32.4	24.4	24.4
29	No analysis					
30	0.8	1.6	5.4	11.6	21.2	59.4
31	23.7	44.6	12.0	5.3	3.4	11.0
32	2.6	28.2	43.2	9.7	3.7	12.6
33	11.7	33.7	31.5	9.4	3.7	10.0
34	0.5	5.9	11.6	17.4	27.4	37.2
35	0.7	13.3	34.9	16.2	13.7	21.2

pearance. Some muscovite is also present in the heavy fraction.

Biotite.—Biotite was very rarely observed under the petrographic microscope, but in mass examination with the binoculars an occasional weathered grain of biotite was seen. Further, on the basis of clear mica flakes which are uniaxial or have a small optic angle, the writer thinks that a small part of the material called muscovite is actually leached biotite.

Chlorite.—Chlorite is a pale green, micaceous, slightly magnetic mineral occurring in small quantity. Though an occasional grain is found in the heavies, chlorite is counted as a light mineral. Its moderate refringence, low birefringence, and positive optical sign determines it as chlorite.

Undetermined minerals.—In the light fraction there are aggregates of very fine micaceous and fibrous materials which vary widely in appearance and probably in mineralogy. Because of the minuteness of the individual particles and because of the presence of abundant opaque included matter, precise mineralogic determinations were not made. It is believed that the aggregates are composed largely

TABLE 5.—*Facies comparison in percent weight by size grades*

Medium Sand				Fine Sand		Very Fine Sand		Silt & Clay	
Sample No.	Channel Facies	Sample No.	Sheet Facies	Channel Facies	Sheet Facies	Channel Facies	Sheet Facies	Channel Facies	Sheet Facies
9	1.3	1	0.0	40.0	1.4	39.4	43.0	19.3	55.6
11	0.9	2	0.3	47.5	9.0	38.0	34.8	13.6	55.9
13	16.1	3	0.6	59.2	21.4	14.3	49.4	10.4	28.6
17	0.4	4	1.2	3.1	18.2	21.0	47.8	75.5	32.8
21	1.2	5	0.7	22.6	15.5	59.1	63.4	17.1	20.4
26	15.8	6	0.1	53.9	1.7	14.2	32.2	16.1	66.0
31	23.7	7	tr.	56.6	tr.	8.7	tr.	11.0	90.0+
32	2.6	8	tr.	71.4	tr.	13.4	tr.	12.6	90.0+
33	11.7	10	0.5	65.2	17.8	13.1	64.8	10.0	16.9
35	0.7	12	4.1	48.2	48.0	29.9	37.3	21.2	10.6
		15	0.2		14.3		47.2		38.3
		16	1.0		35.1		39.6		24.3
		18	15.0		48.2		27.3		9.5
		20	0.4		8.1		32.3		59.2
		22	0.3		7.2		59.8		32.7
		23	0.5		3.7		15.7		80.1
		24	0.8		18.0		42.6		38.6
		25	1.4		16.5		46.9		35.2
		27	2.4		50.3		33.1		14.2
		28	0.4		16.4		32.0		51.2
		28A	0.1		18.7		56.8		24.4
		30	0.8		7.0		32.8		59.4
		34	0.5		17.5		44.8		37.2
Avg.	7.4		1.3	46.3	16.4	25.1	19.2	20.7	44.2

of kaolinite, sericite, chlorite, biotite, illite, cryptocrystalline quartz, and perhaps other minerals. For purposes of counting, this material is arbitrarily called chloritic matter. It probably represents advanced alterations of such minerals as the amphiboles and pyroxenes which might logically have been expected in this suite but which do not appear.

DISCUSSION

Mineral and Textural Variations from a Stratigraphic Standpoint

The mineral assemblages are much the same throughout the vertical range of the section sampled, but there are minor differences. Texturally, the sandstones are never significantly coarser than fine sand and are usually well sorted with more than fifty percent of a given sample being within one Wentworth size grade division.

Garnet varies vertically through the section from less than 1 per cent to almost 50 per cent of the non-opaque heavies. It is rare in all three samples in the Wheeler, and is noticeably abundant in the Myrick Station, Marshall, Ardmore, and Abingdon samples. Examination of figure 2 showing the stratigraphic ranges of the minerals shows an inconstant increase in garnet upward in the section. Studies by Bramlette (1929) and Dryden and Dryden (1946), call attention to the solubility of garnet, which suggests the possibility that the more marked variations in the quantity of the garnet are related to the permeability of that particular sandstone in the area sampled.

Barite, although varying from zero to almost 90 per cent of the non-opaque heavies, shows a distinct concentration in the three samples from the Wheeler cyclothem and a more sporadic concentration in the Blackjack Creek cyclothem.

TABLE 6.—*Percent weight presented stratigraphically by size grades*

Formation	Facies	Sample No.	Medium Sand	Fine Sand	Very fine Sand	Silt & Clay
Post Hertha	Sheet	5	0.7	15.5	63.4	20.4
Cooper Ck.	Sheet	4	1.2	18.2	47.8	32.8
Worland	Sheet	3	0.6	21.4	49.4	28.6
Do.	Sheet	6	0.1	1.7	32.2	66.0
Do.	Sheet	16	1.0	35.1	39.6	24.3
Do.	Channel	17	0.4	3.1	21.0	75.5
Coal City	Sheet	2	0.3	9.0	34.8	55.9
Myrick Stn.	Sheet	7	tr.	tr.	tr.	90.0+
Do.	Sheet	12	4.1	48.0	37.3	10.6
Do.	Sheet	18	15.0	48.2	27.3	9.5
Marshall	Sheet	8	tr.	tr.	tr.	90.0+
Higginsville	Sheet	22	0.3	7.2	59.8	32.7
Blackjack Ck.	Sheet	1	0.0	1.4	43.0	55.6
Do.	Channel	9	1.3	40.0	39.4	19.3
Do.	Channel	•11	0.9	47.5	38.0	13.6
Do.	Sheet	19	No analysis			
Do.	Channel	21	1.2	22.6	59.1	17.1
Do.	Sheet	23	0.5	3.7	15.7	80.1
Do.	Sheet	24	0.8	18.0	42.6	38.6
Do.	Channel	26	15.8	53.9	14.2	16.1
Do.	Channel	32	2.6	71.4	13.4	12.6
Do.	Channel	35	0.7	48.2	29.9	21.2
Bedford	Sheet	10	0.5	17.8	64.8	16.9
Do.	Sheet	25	1.4	16.5	46.9	35.2
Wheeler	Sheet	15	0.2	14.3	47.2	38.3
Do.	Sheet	20	0.4	8.1	32.3	59.2
Do.	Sheet	34	0.5	17.5	44.8	37.2
Ardmore	Channel	31	23.7	56.6	8.7	11.0
Abingdon	Sheet	27	2.4	50.3	33.1	14.2
Do.	Sheet	28A	0.1	18.7	56.8	24.4
Munterville	Channel	13	16.1	59.2	14.3	10.4
Do.	Sheet	28	0.4	16.4	32.0	51.2
Do.	Sheet	30	0.8	7.0	32.8	59.4
Do.	Channel	33	11.7	65.2	13.1	10.0

Furthermore, barite is not found in any of the samples from Guthrie, Monroe, and Wapello counties, thus confining its occurrence, in a general way, to the broad central part of the area sampled. Barite is abundant only in the sheet facies, is generally absent in the channel facies, and, if present, occurs in quantities less than 1.5 per cent. These several observations suggest that the barite is authigenic and is controlled in its local occurrences, at least in part, by the permeability of the containing beds.

Chloritoid occurs in quantities greater than 1 per cent only in those formations including and older than the Higginsville.

Zircon and tourmaline show no noteworthy variations or trends.

The titanium minerals, leucoxene, anatase, and rutile, are very abundant, ordinarily comprising from 35 to 55 per cent of the total heavies. Both authigenic and detrital varieties are believed to be present. No significant variations are discernible.

In binocular examination the micaceous material seems more abundant in the coarser samples. This is due not as much to the greater numerical abundance of the mica in the coarser sands, as to the fact that the mica flakes have larger diameters and are therefore much more noticeable in the coarser material.

The average size of the material in the

sands from the channel facies is, with few exceptions, distinctly more coarse than that of the sheet facies. Table 5 shows this very strikingly. Well over half the material in the channel facies is classified as fine and very fine sand, whereas over half the material in the sheet facies is classified as very fine sand, and silt and clay. The Blackjack Creek samples appear, on the average, coarser than samples from the other cyclothems, but this probably is merely a reflection of the relatively higher number of samples from the channel facies of the Blackjack Creek. The presence of numerous prominent channels at this stratigraphic position has been pointed out by Cline (1938).

Environment of Deposition

To the writer the uniformity of the mineral suite, coupled with that of the textures of the sands, is indirect evidence of marine deposition. The consistently good sorting of the basal member of each cyclothem regardless of the stratigraphic position or the size grades involved, the wide lateral extent without marked lithologic change, and the absence of less stable minerals, indicate to the writer that the sediments were long exposed to winnowing agents which effected this uniformity before final burial. The writer visualizes the environment of deposition as one in marine waters of no great depth with opportunities for repeated reworking. The presence of the channels poses no great problem; they could be inherited from a former land surface or they could be marine channels.

Immediate Source of Sediments

Pre-existing sediments probably furnished most of the material for these Iowa sediments. Evidence consists of the lack of unstable minerals, except apatite, and the marked variation in degree of wear shown by the several abundant minerals: notably, zircon, garnet, and tourmaline. The zircon in any one sample may show variations from much rounded, worn, discolored, hardly recognizable grains to clear crystals apparently untouched by chemical change or abrasion. Likewise, the garnet shows all degrees of wear. In the case of the tourmaline, the colorless, cloudy-blue, and green grains seem least worn, whereas the browns, dark greens, and blues usually are well worn. The blue variety is almost never found with crystal faces remaining. That these variations may in part be due to obscure chemical differences is recognized, as is also the possibility that considerable solution has taken place because of long exposure to detrimental environmental factors operative before final burial. Differentials in permeability have doubtless affected the appearance and abundance of some species. Even so, the abundance of completely unweathered grains suggests that the area was receiving some material from primary and metamorphic crystalline rocks.

Ultimate Provenance Areas

The writer is not able to assign specific provenance areas from the results of this limited study. The association of garnet, chloritoid, staurolite, and muscovite, points to metamorphic rocks of moderate rank as one source of sediments. On the other hand, the quartz inclusions, when classified according to Mackie (1896), fail to indicate anything other than granitic terranes as the ultimate source. This apparent contradiction points to the conclusion that both grantic and metamorphic terranes were contributors. Logical provenances include the garnet, chloritoid, and staurolite bearing rocks of the southern Canadian shield (Van Hise, 1897). Also this mineral assemblage is found in older Paleozoic and pre-Cambrian crystalline rocks in the northern Appalachian regions which are exposed at the present time and may have been exposed in the Pennsylvanian. Although these mineral associations are pointed out it is thought that the present study does not in any way indicate a specific provenance area; indeed, it is logical to suppose that several provenances were

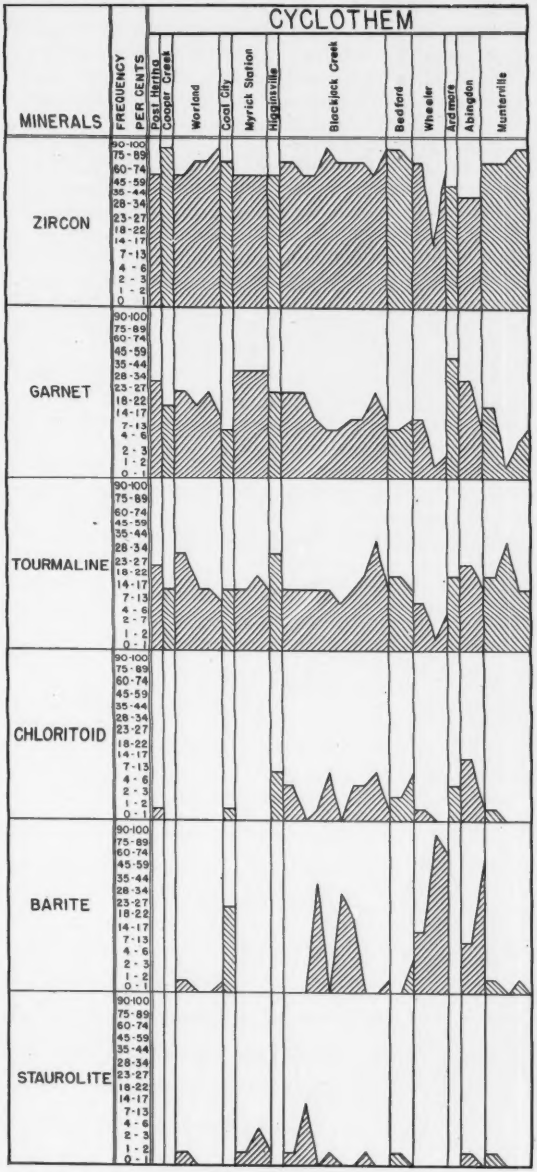

FIG. 2.—Heavy mineral range table
(exclusive of opaques and titanium minerals).

contributing. As has been pointed out by Twenhofel (1941), surface and subsurface lateral sampling in several directions up to the areas of crystalline rock should determine contributing provenances. Such studies, augmented by detailed textural studies, should give much information regarding sedimentary conditions and paleogeography in Pennsylvanian time.

CONCLUSIONS

A statistical mineral study and size grade analysis of the basal sandstone members of various cyclothems from the Des Moines series of south-central Iowa affords the following conclusions:

1. The heavy mineral suite consists of zircon, garnet, tourmaline, chloritoid, barite, staurolite, apatite, rutile, anatase, leucoxene, magnetite, hematite, pyrite, and possibly very small quantities of other minerals. Zircon, garnet, tourmaline, and leucoxene are abundant.

2. The light minerals are quartz, orthoclase, microcline, plagioclase, muscovite, biotite, chlorite, and minor quantities of undetermined material.

3. Quartz is the major constituent, averaging about 85 per cent by grain count after removal of cementing material. Feldspar, mica, and undetermined chloritic material comprise most of the remainder. Numerically the heavy minerals are insignificant.

4. Results of correlative value were not obtained, although locally an abundance of barite and a near absence of garnet characterize the Wheeler cyclothem.

5. The sandstones are uniformly well sorted and are composed almost entirely of material of smaller diameter than one-fourth mm. Many of the so-called basal sandstones are really siltstones.

6. The channel facies are composed of distinctly larger material than the sheet facies.

7. The sandstones were largely derived from pre-existing sediments, but probably a small amount of material was continuously supplied from crystalline rocks.

8. Until similar studies are expanded provenance areas cannot be fixed.

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Sample Localities

Sample No. 1. Cyclothem: Blackjack Creek. Facies: Sheet.
Location: SW¼ sec. 12, or NW¼ sec. 13, T. 75 N., R. 26 W. Right creek bank at N foot of high hill to the SE, about 1 mile N of St. Charles, Madison County, Iowa.
Sample No. 2. Cyclothem: Coal City. Facies: Sheet.
Location: SW¼ NW¼ sec. 26, T. 75 N., R. 26 W. In creek bank SW of St. Charles, Madison County, Iowa.
Sample No. 3. Cyclothem: Worland. Facies: Sheet.
Location: SW¼ NW¼ sec. 26, T. 75 N., R. 26 W. In creek bank SW of St. Charles, Madison County, Iowa
Sample No. 4. Cyclothem: Cooper Creek. Facies: Sheet.
Location: SE¼ sec. 27, T. 76 N., R. 27 W. Madison County, Iowa.
Sample No. 5. Cyclothem: Unidentified sandstone above Hertha limestone in Missouri series. Facies: Sheet (?).
Location: NE¼ NW¼ sec. 12, T. 24 N., R. 27 W. Madison County, Iowa.
Sample No. 6. Cyclothem: Worland. Facies: Sheet.
Location: NE¼ NE¼ sec. 19, T. 78 N., R. 30 W. Guthrie County, Iowa.
Sample No. 7. Cyclothem: Myrick Station. Facies: Sheet.
Location: SE¼ sec. 5, T. 79 N., R. 30 W. Guthrie County, Iowa.
Sample No. 8. Cyclothem: Marshall. Facies: Sheet.
Location: SE¼ sec. 5, T. 79 N., R. 30 W. Guthrie County, Iowa.
Sample No. 9. Cyclothem: Blackjack Creek. Facies: Channel.
Location: Center of the W line of sec. 9, T. 79 N., R. 30 W. Guthrie County, Iowa.
Sample No. 10. Cyclothem: Bedford. Facies: Sheet.
Location: NE¼ SW¼ sec. 8, T. 79 N., R. 30 W. Guthrie County, Iowa.
Sample No. 11. Cyclothem: Blackjack Creek. Facies: Channel.
Location: NE¼ SW¼ sec. 8, T. 79 N., R. 30 W. Guthrie County, Iowa.
Sample No. 12. Cyclothem: Myrick Station. Facies: Sheet.
Location: Center of the S line of NE¼ SW¼ sec. 25, T. 79 N., R. 30 W. In road ditch, Guthrie County, Iowa.
Sample No. 13. Cyclothem: Munterville. Facies: Channel.
Location: SW¼ sec. 4, T. 78 N., R. 29 W. In road ditch on S side of bridge, Dallas County, Iowa.
Sample No. 14. Cyclothem: Ardmore. Facies: Sheet.
Location: SW¼ SW¼ sec. 9, T. 78 N., R. 29 W. Along creek, Dallas County, Iowa.
Sample No. 15. Cyclothem: Wheeler. Facies: Sheet.
Location: SW¼ SW¼ sec. 9, T. 78 N., R. 29 W. Along creek, Dallas County, Iowa.
Sample No. 16. Cyclothem: Worland. Facies: Sheet.
Location: East central portion of SW¼ sec. 20, T. 78 N., R. 28 W. Dallas County, Iowa.
Sample No. 17. Cyclothem: Worland. Facies: Channel.
Location: NE¼ NW¼ sec. 29, T. 78 N., R. 28 W. Dallas County, Iowa.
Sample No. 18. Cyclothem: Myrick Station. Facies: Sheet.
Location: NW¼ NW¼ sec. 15, T. 78 N., R. 26 W. Dallas County, Iowa.
Sample No. 19, Cyclothem: Blackjack Creek. Facies: Sheet.
Location: East central portion of sec. 30, T. 78 N., R. 26 W. Bluff of Raccoon River near Booneville, Dallas County, Iowa.
Sample No. 20. Cyclothem: Wheeler. Facies: Sheet.
Location: Center portion of sec. 29, T. 78 N., R. 25 W. In left bank of Raccoon River just below bridge at Commerce, Polk County, Iowa.
Sample No. 21, Cyclothem: Blackjack Creek. Facies: Channel.
Location: North line of NW¼ NW¼ sec. 26, T. 75 N., R. 24 W. In road cut, Warren County, Iowa.
Sample No. 22. Cyclothem: Higginsville. Facies: Sheet.
Location: West line of SW¼ NW¼ sec. 25, T. 75 N., R. 24 W. In road ditch, Warren County, Iowa.
Sample No. 23. Cyclothem: Blackjack Creek. Facies: Sheet.
Location: NE¼ sec. 2, T. 75 N., R. 23 W. Gully beside road, Warren County, Iowa.
Sample No. 24. Cyclothem: Blackjack Creek. Facies: Sheet.
Location: NE¼ sec. 2, T. 75 N., R. 23 W. Gully beside road, Warren County, Iowa.
Sample No. 25. Cyclothem: Bedford. Facies: Sheet.
Location: NE¼ sec. 2, T. 75 N., R. 23 W. Gully beside road, Warren County, Iowa.
Sample No. 26. Cyclothem: Blackjack Creek. Facies: Channel.
Location: Center of S line of sec. 16, T. 74 N., R. 22 W. Warren County, Iowa.

Sample No. 27. Cyclothem: Abingdon. Facies: Sheet.
Location: Along E line of NE¼ SE¼ sec. 14, T. 74 N., R. 22 W. Warren County, Iowa.
Sample No. 28. Cyclothem: Munterville. Facies: Sheet.
Location: Along E line of NE¼ SE¼ sec. 14, T. 74 N., R. 22 W. Warren County, Iowa.
Sample No. 28A. Cyclothem: Abingdon. Facies: Sheet.
Location: NE corner of SE¼ sec. 16, T. 74 N., R. 21 W. Marion County, Iowa.
Sample No. 29. Cyclothem: Munterville. Facies: Sheet.
Location: Center of W line of sec. 25, T. 75 N., R. 21 W. Railroad cut bank, Marion County, Iowa.
Sample No. 30. Cyclothem: Munterville. Facies: Sheet.
Location: Center of W line of sec. 25, T. 75 N., R. 21 W. Rock Island R. R. cut bank, Marion County, Iowa.
Sample No. 31. Cyclothem: Ardmore. Facies: Channel.
Location: Center of SE¼ sec. 10, T. 73 N., R. 18 W. West of Lovilla, Monroe County, Iowa.
Sample No. 32. Cyclothem: Blackjack Creek. Facies: Channel.
Location: Center of sec. 10, T. 73 N., R. 18 W. Road cut on County Hywy. L, half a mile west of Lovilla, Monroe County, Iowa.
Sample No. 33. Cyclothem: Munterville. Facies: Channel.
Location: SE¼ NW¼ sec. 11, T. 71 N., R. 13 W. Cliff in R.R. cut bank at Cliffland, Wapello County, Iowa.
Sample No. 34. Cyclothem: Wheeler. Facies: Sheet.
Location: SW corner of sec. 21, T. 76 N., R. 23 W. Warren County, Iowa.
Sample No. 35. Cyclothem: Blackjack Creek. Facies: Channel.
Location: SE corner of sec. 33, T. 76 N., R. 22 W. Warren County, Iowa.

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FIGS. 1–7, APRIL, 1950

BOTTOM DEPOSITS AT THE MOUTH OF WAKASA BAY, JAPAN, AND ON THE ADJACENT CONTINENTAL SHELF[1]

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ABSTRACT

The petrographic characteristics of the bottom sediments and associated organisms in the Wakasa Bay region are described. These are related to present topography, depth, and water characteristics, and also in part reflect the geological history of the region.

INTRODUCTION

The bottom topography of the seas surrounding Japan is quite complicated, there being numerous banks on and near the continental shelf around the chain of Japanese Islands. Many submarine valleys can be recognized on the continental shelf. The peaks and valleys on the sea bottom provide important fishing centers and are of special interest from the view point of oceanography, because they are amply endowed with a variety of oceanic conditions and exhibit notable peculiarities in the distribution of fauna. From a geological point of view, the topography and the geology of this area present many problems whose solution will clarify the geological structure and the recent geological history of the Japanese arc. The banks and the submarine deposits surrounding them, in particular, display characteristics somewhat different from the ordinary deposits on the continental shelf.

A comparison of these deposits with those of the nearby continental shelf which is subject to the same oceanic conditions is likely to yield valuable results in the solution of many problems; for example, regional unconformities, and correlation among contemporaneous deposits of different facies.

The Urashima, Gentatsu, Matsudashi, Oguri, and other banks at the mouth of Wakasa Bay are a part of a chain of banks longitudinally arranged along the coast of Honshû. They occupy the central portion of the bay. On the continental shelf near these banks can be seen a scattering of islands and small banks. Large rivers also flow into the sea and thus make this area suitable for a comparative study of the bottom characters of the banks and the continental shelf. A detailed research was thus made of the bottom character of this region with the object of ascertaining the peculiar characteristics of the submarine deposits which constitute the banks.

BOTTOM TOPOGRAPHY OF WAKASA BAY

Wakasa Bay is situated in central Honshû between 135° 10′ E and 35° 30′ N and it faces the Japan Sea (fig. 1). Urashima Bank lies at the mouth of the bay, off the Tango Peninsula, while Gentatsu Bank is off Cape Anto. These banks stretch in a northeast-southwest direction, but their major axes trend in various directions and constitute a sort of echelon structure. The banks all have steep slopes toward the sea bottom, but have a flat surface between depths of 100 and 120 meters. There are also flat plains on the continental shelf between the depths of 200–230 m, 100–120 m, 80–100 m, and 40–60 m,

[1] EDITOR'S NOTE: this paper was documented with several detailed maps, showing distribution of sediment types and of organisms, which were not included because of the limited space available in the *Journal*.—J.L.H.

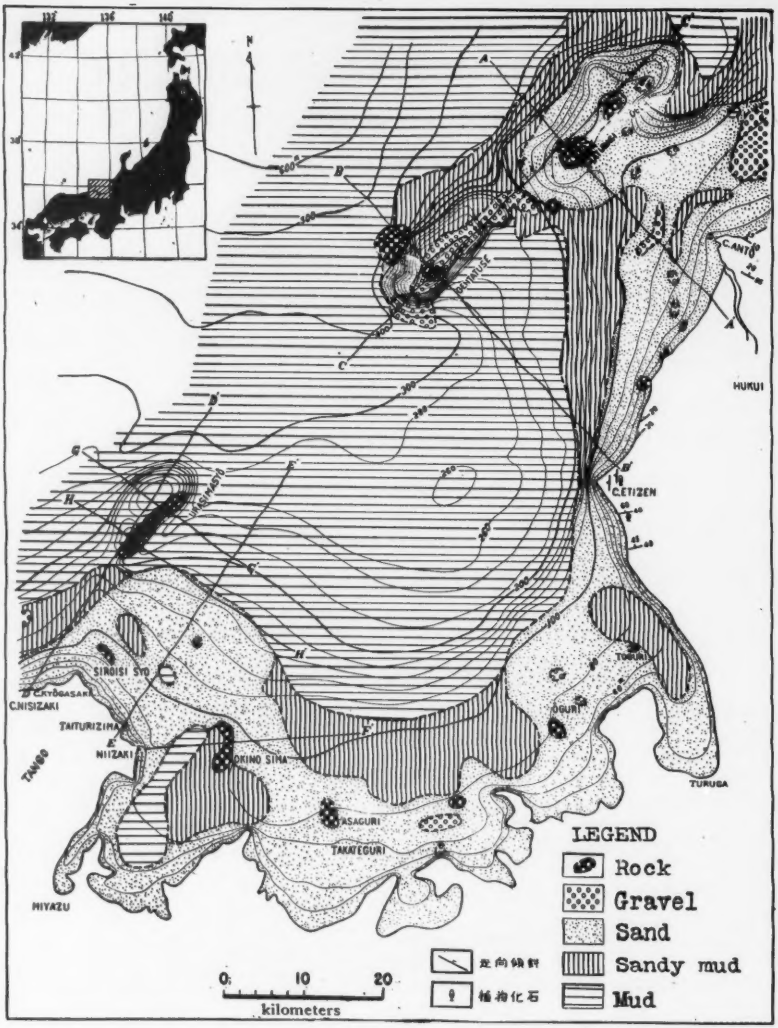


FIG. 1.—Wakasa Bay topography and bottom materials. Based on Japanese Navy Hydrographic Department Chart No. 139.

with small banks and isles located on the flat plains between 40–60 m. The submarine topography of the bay is shown in figures 1 and 2.

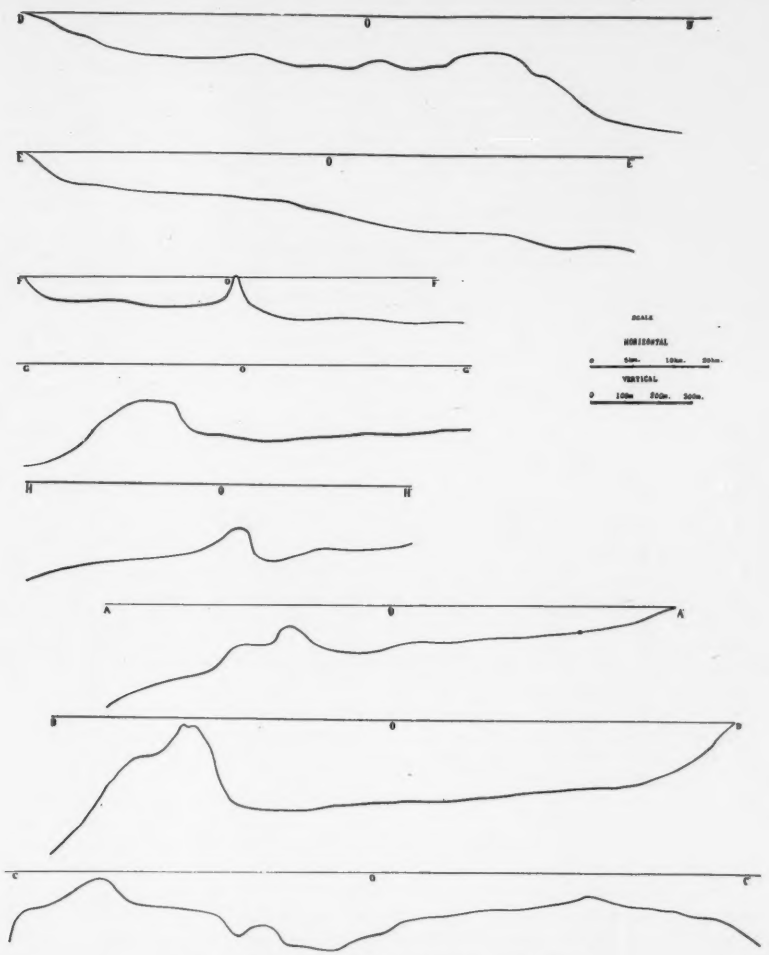


FIG. 2.—Cross sections along lines shown in figure 1.

TOPOGRAPHY AND GEOLOGY OF THE COASTAL REGION AND OCEANIC CONDITION

Topography

In the coastal region there is a flat plain of about 600 m height, which has been dislocated by block faulting. In addition there are two sets of coastal terraces along the northern coast of the Tsuruga bay in the interior of Wakasa Bay. Deltas are not well developed at the mouth of the river.

Geology

In this area pre-Tertiary formations are overlain by shell and plant bearing Tertiary strata which are penetrated by or interbedded with liparite, porphyrite, andesite and agglomerate. Pleistocene deposits on them at some places consist of gravels, sand, and clay. They are generally horizontal, but in the vicinity of Antozaki the deposits dip 20°NE and strike N 85°W. Alluvium is generally represented by sand and gravel on flood plains but in the vicinity of Antozaki alluvial blue clay containing peat is found to overlie the Pleistocene unconformably.

Oceanic Condition

In the summer season the temperature and salinity are respectively 26°C. and 32.4°/$_{oo}$ at sea surface to 50 m depth, and 19°C. and 34.6°/$_{oo}$ between 50 and 100 m. The surface water of high temperature and salinity belongs to the Tsushima Current but below 200 m there is a cold water mass peculiar to the Japan Sea, with a temperature of 0° to 3°C. and a salinity of 34.5°/$_{oo}$. The velocity of the oceanic current in the bay is 1.5–2 km/hr off the Kyôgasaki and is 1.5 km/hr at Antozaki at the mouth of the bay. Within the bay the current forms a large whirlpool, flowing in clockwise direction at the rate of 0.4–1.0 km/hr at a depth of 50 m and of 0.1–0.3 km/hr at a depth of 200 m.

STUDY OF MATERIALS AND BOTTOM SAMPLES

Bottom samples were collected at 170 stations on the banks and shelves during 1935 to 1938. Additional samples were procured from 7 stations by the Sôyô-Maru, from 212 stations by the Fisheries Experimental Station in Fukui Prefecture, and materials from 334 other stations are in the Suirobu (Hydrographical Department of the Japanese Navy) amounting to 623 in total. Owing to the small size of the samples in the Suirobu collection only macroscopic observations were made of them.

The samples were classified into organisms, their remains, and inorganic matter. Taxonomic identification was made on the organisms and their frequency of occurrence was determined. The inorganic matter was separated into rock, gravel, sand and mud. Macroscopic examination and thin-section studies were made of rocks and gravels, while mechanical analyses were made on sand and mud. Next, the distribution of the kinds of bottom samples and their relationship to the distribution of organisms was investigated.

For this study, Chart No. 139 published by the Suirobu was used, from which a chart of bottom samples was compiled (fig. 1). The redrawn chart is somewhat different from the original Suirobu map.

BOTTOM CHARACTER AT THE MOUTH OF WAKASA BAY

Rocky Floor

The rocky floor is exposed at 72 stations where rock fragments were procured by dredging. It is also presumed to be exposed at 15 other stations. Of these 87 stations, the maximum depth is 400 m and the minimum 10 m. The rocky floor is most commonly exposed on the banks and in their vicinity, and also in shallow areas near the coast as shown in the map.

Organisms are frequently attached to these rocky floors, some of which appear to be covered with mud, and others by sand and gravel. Many soft rocks of the floor are bored by organisms. Twenty-five per cent of the number of rock stations between 0–50 m contain bored rocks 33 per cent at 100–150 m, and 58.3 per cent at 200–215 m. The ratio of the number of such stations to the total with rocky bottom in the whole bay was 47.2 per cent. Notwithstanding the fact that erosion by currents is negligible in the sea below 100 m, traces of boring by organisms on rock are found at such a depth, showing that there are destructive agencies even at considerable depths.

Among 72 stations where rock fragments were collected, adhering organisms were found in samples from 56 stations (77.7 per cent). Altogether 100 per cent of the samples between 0–50 m contain organisms, 80 per cent at 50–100 m, 80 per cent at 100–150 m, 58.3 per cent at 150–200 m, and 66.6 per cent at 200–250 m. These benthos vary in kind according to depth. Calcareous algae are common at 50–100 m; brachiopoda, corals, and molluscs at 100–150 m. (See fig. 7.)

Except at the Toguri Bank at the mouth of the Tsuruga Bay, the rock samples are all Tertiary sedimentaries or igneous rocks which penetrate the sedimentaries. Andesite, basalt, and liparite were collected at the shallowest stations as well as from on the steep slope of the Gentatsu and Matsudashi banks. The occurrences suggest that the igenous rocks are exposed on the sea floor as on the land.

Sedimentary rocks were collected at many stations on the banks and at some on the continental shelf. They include conglomerates, tuff, coarse sandstone, calcareous sandy shale (with fossil mollusca and plants), tuffaceous calcareous shale (containing fossil Foraminifera) and diatomaceous shale, like those in the Tertiary formations around Wakasa Bay. Fossils in these samples (IW.St.1) consisted of *Quercus*, *Arca*, *Dosinia*, and *Coscinodiscus*. Unfortunately, their imperfect preservation did not permit determination of their geological age. Figure 1 shows the distribution of the rocky floor.

The basement of the banks in Wakasa Bay consists of a Tertiary formation covered by a thin layer of sand and gravel. Submergence to their present position is thought to have taken place after the deposition of the gravel layer.

Gravels

General.—Gravel was obtained at 213 stations. Among these 123 are on the continental shelf, 83 on the banks and their vicinity at the mouth of the bay, and the remaining 7 from outside the bay. The distribution of gravel is intimately related to submarine topography. Gravel is seldom found in the depressions between the banks and the continental shelf. Gravel areas can be classified into two groups—those on the banks and their vicinity and those on the continental shelf. On the shelf such areas are crowded on the Fukui side near Cape Anto at the mouth of Kuzuryu River and on the flat of the continental shelf off the coast.

Besides examining the shape and kind of gravel, the largest obtained at each station was studied as to weight, major and minor diameters and thickness, external aspect, lithic characters and presence or absence of organisms. The following facts were noted:

Relation of Gravel Weight to Sea Depth.—The average weight of the selected gravels from depths of 0 to 50 m was 3.7 gm; 50–100 m, 3.6 gm; 100–200 m, 20.5 gm; 200–250 m, 11.8 gm; and from 250 m or more, 1.5 gm. The average weight reaches a maximum between depths of 100 and 150 m. It decreases somewhat between 150 and 200 m but increases between 200 and 250 m and thereafter decreases abruptly.

Gravels with organisms (believed to have been exposed on the floor) weigh on the average 1.0 gm at depth from 0 to 50 m, 10.4 gm at 50–100 m, 67.3 gm at 100–150 m, and 26.5 gm at 200–250 m. The maximum average weight is at the depth from 100 to 150 m. Of gravels without organisms (believed to have been embedded within the mud floor) the average weight is 4.1 gm at depths of 0–50 m, 1.8 gm at 50–100 m, 1.4 gm at 100–150 m, 3.5 gm at 150–200 m, 2.0 gm at 200–250 m, and 1.5 gm at below 250 m. The gravels are thus largest at the depths of 50 m or less. The ratio of the number of places where gravels with organisms were procured to the total of stations where gravels were found is 12.4 per cent at depths of 0–50 m, 29.8 per cent at 100–200 m, and 40.0 per cent at 200 to 250 m.

At a distance of 5 km from the coast

the average weight of the largest gravels from the various stations is 2.7 gm. The weight attains its maximum at a distance from 15 to 20 km from the coast, weighing 12 gm, thence on it decreases. When the same calculation was made with reference to gravels with and without organisms, it was found that the average weight of the former attains its maximum (42 gm) at 10–15 km and that of the latter (2.3 gm) at 0.5 km from shore. Incidentally it may be mentioned that the average weight of the latter is 4.5 gm at 15–20 km, but the paucity of number of stations where such gravels were collected makes questionable the reliability of this average.

In summarizing these facts it can be said that it is quite abnormal that gravel on the continental shelf increases in sizes in the open sea off-shore as depth increases, but this peculiarity is general in the distribution of gravel in the seas around Japan. While the gravel exposed on the bottom becomes larger off-shore, that embedded in the mud floor is largest in shallow waters near the coast and smallest off the shore, but it becomes somewhat larger on the continental slope.

The maximum depth of the gravel found in the environs of the banks is 658 m. Its average weight from the Gentatsu, Oguri, Urashima, and other banks and the surroundings is 4.5 gm at depths of 0–50 m, 16.7 gm at 50–100 m, 35.5 gm at 100–150 m, 16.3 gm at 150–200 m, 15.3 gm at 200–250 m, 63.3 gm at 250–300 m, 1.3 gm at 300–350 m, 0.8 gm at 400–450 m, and 3.0 gm at 450–500 m. It is noteworthy that this gravel is heavier than that of the same depth on the continental shelf. More than ten samples containing gravel were procured in every zone of 50 m depth. Between depths of 50 m and 250 m, gravel was obtained from more than ten stations in each of the 50 m zones. The average size of the gravel was largest in the zone from 100 to 150 m.

The average weight of gravel with organisms from the banks was 4.5 gm in depths from 0 to 50 m, 20.3 gm at 50–100 m, 51.4 gm at 100–150 m, 23.1 gm at 150–200 m, 22.1 gm at 200–250 m, that of gravel without organisms was 7.0 gm at 50–100 m, 13.0 gm at 100–150 m, 32.0 gm at 150–200 m and 26.5 gm at 200–250 m. Thus, gravel with organisms is always larger than that without organisms regardless of depth. The ratio of the number of stations where gravel is exposed on the bank to the total of spots where gravel was procured is 100 per cent for the depth 0–50 m, 85.6 per cent for 50–100 m, 74.1 per cent for 100–150 m, 61.5 per cent 150–200 m, 58.3 per cent for 200–250 m, and 25.0 per cent for 250–300 m. All the percentages are high when compared with those obtained on the continental shelf.

Shape of gravel and its lithology.—Gravel on the shelf as well as on the banks generally is well water-worn and none is striated. There are, however, some Tertiary sedimentary rock gravel which is not well water-worn or bored by organisms. The gravels comprise: (1) Pre-Tertiary sedimentary rocks—chert, radiolarian chert, quartzite, sandstone, clay-slate, sandy shale and others which are exposed on land around Wakasa Bay; (2) Granite associated with them; (3) Andesite, porphyrite, basalt, liparite, quartz-porphyry porphyrite, obsidian, and other igneous rocks commonly met with in the Tertiary terrain.

The general assemblage of these rocks in gravels does not differ in different places, but it is noted that gravels of soft sedimentary Tertiary rocks are most common in the vicinities of the banks. These—even those of the pre-Tertiary rocks—are not, presumably, gravels formed directly from their mother rocks but are reworked gravels from the conglomerate beds in the Tertiary formation. Gravels of Tertiary rock are mostly distributed around the banks.

Organisms attached to the gravel.—It is noted that bryozoans are distributed regardless of depth while brachiopods are restricted to depths from 100 to 150 m. The distribution of other groups of organisms is summarized in figure 6.

In conclusion it should be noted that gravels in the bottom samples consist of (1) those transported by rivers or formed through the action of waves, (2) those originating on the banks, (3) those in the submerged gravel bed which is intimately related to the origin of the flat bottom.

Distribution of Sand and Mud According to Grain-Size

Taking 20 grams of sand and mud sifted through a sieve with 2 mm mesh, mechanical analyses were made by the method of the Soil Test Committee of the Railroad Department. The collection was classified according to this method into sand (2 mm–0.074 mm in diameter), silt (0.074–0.005 mm) and clay (less than 0.005 mm). Sand was classified further into five grades employing Tyler's standard sieve [14 mesh (2.0–1.168 mm), 28 mesh (1.168–0.589 mm), 48 mesh (0.598–0.295 mm), 100 mesh (0.295–0.147 mm), and 200 mesh (less than 0.147 mm)].

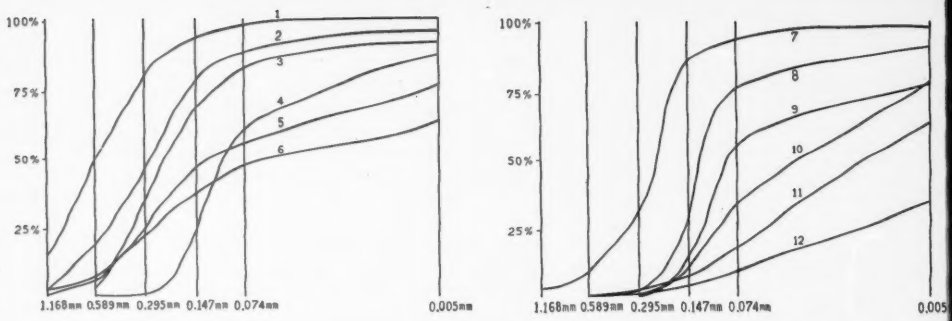
The weight percentage of each class of material was then calculated for each station from which bottom samples were obtained. For each grade (or class) according to size, the stations yielding the percentage values of 1, 10, 20, 30, 40, 50 per cent were contoured together on the map. The surveyed area was thus classified into A (0–1 per cent), B (1–10 per cent), C (10–20 per cent), D (20–30 per cent), E (20–40 per cent), F (40–50 per cent), and G (more than 50 per cent) zones. Among the maps the most significant four (1.168–0.589 mm, 0.295–0.147 mm, 0.074–0.005 mm and less than 0.005 mm) are shown in this paper.[1]

Glancing at these and the other maps not shown here, it was noted that: (1) Coarse grains (0.589–0.295 mm or more) are densely crowded together either at places of upwelling or where the oceanic current is strong, (2) those in the size-grade of 0.295–0.147 mm are distributed in the vicinity of Cape Anto in a direction perpendicular to the oceanic current but extending systematically on the lateral sides of this axis, and (3) the distribution of fine-grained (0.147–0.074 mm) sand reveals the effect of topography, although, on the continental shelf on the east side of the Tango Peninsula, fine grained sand is abundant even on shallow bottom where the current is circular and the water stagnant.

Judging from these salient facts it may be concluded that for the bottom material to be moved by the current the limit is reached when the grain size of 0.295–0.14 mm is attained, the coarse sand of 0.589–0.295 mm or more in diameter being residual. If the abnormal distribution of gravel aforementioned is brought into consideration, it may be suggested that coarse sands are derived from a sand formation in the bay and not from the adjacent land. In this connection it should be noted that sand grains larger than 0.147 mm can hardly be transported by bottom current with a velocity of 4–12 cm/sec at the depth of 200 m in the area under consideration. Coarse and fine sands are distributed in strip-like pattern off Cape Anto. This peculiar mode of distribution is probably due to transportation by oceanic current of sediment (or mud) brought down by river.

Using semi-logarithmic section paper, cumulative curves for weight percentage of mud and sand were drawn and the median and deviation values were calculated. With these, Phi-median and Phi-deviation maps were prepared and a cumulative curve figured for each station. The curves obtained can be classified into 13 kinds, among which only the typical ones are illustrated here (fig. 3). The median value is larger than 0.1 mm in the 1st-7th kind while in the 9th–12th kind, it is less than 0–1 mm. The 13th kind is abnormal. The 1st and 2nd kinds lie on the banks and the flat of the continental shelf off the shore; the 5th and 6th are distributed irregularly in the same area; the 4th, 7th, and 8th kinds are on the middle part of the continental slope; and the 9th to 12th kinds are dis-

[1] EDITOR'S NOTE: It was not possible to include these detailed maps, because of limited space.

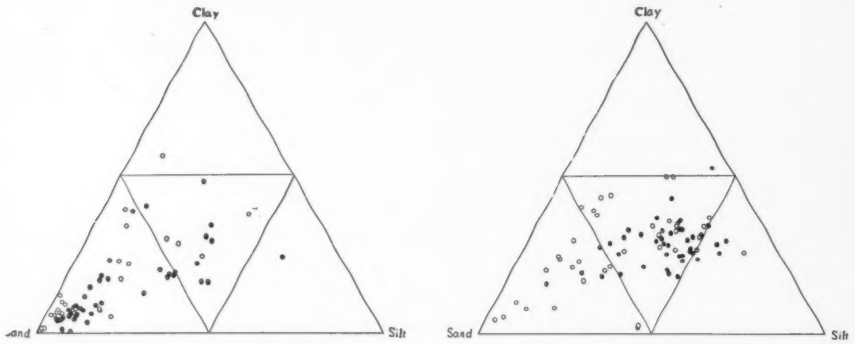


A.—Curves 1–6 B.—Curves 7–12

FIG. 3.—The types of cumulative curves.

tributed on the continental slope and in abyssal depths. The 11th kind, on the contrary, is on the shallow part of the continentals slope instead of at the deepest part of the area. This unexpected distribution is presumably due to the oceanic current.

The percentage of sand, silt, and clay for all samples in each 100 meter depth range was plotted on a triangular coordinate diagram. Within each range of depth, stations on the banks were distinguished from those on the continental shelf (fig. 4). The diagram shows that there is far less sand on the shelf than on the banks in the same depth. In other words, coarse sands are distributed to greater depths on the banks and their surroundings than on the shelf. This fact coincides with the distribution of gravels according to size and weight. Incidentally, if only mud and sand from the places where gravel is obtained or where the rocky floor is exposed are plotted on triangular co-ordinates, it is seen that sand accounts for 80 per cent of the content of samples from most places where gravel was obtained, and the places in which



A.—Depth 100–200 m. B.—Depth 200–300 m.

FIG. 4.—The bottom deposits plotted on triangular co-ordinate diagrams showing percentages of sand, silt, and clay. Dot indicates stations on Continental Shelf; circle indicates stations on the bank.

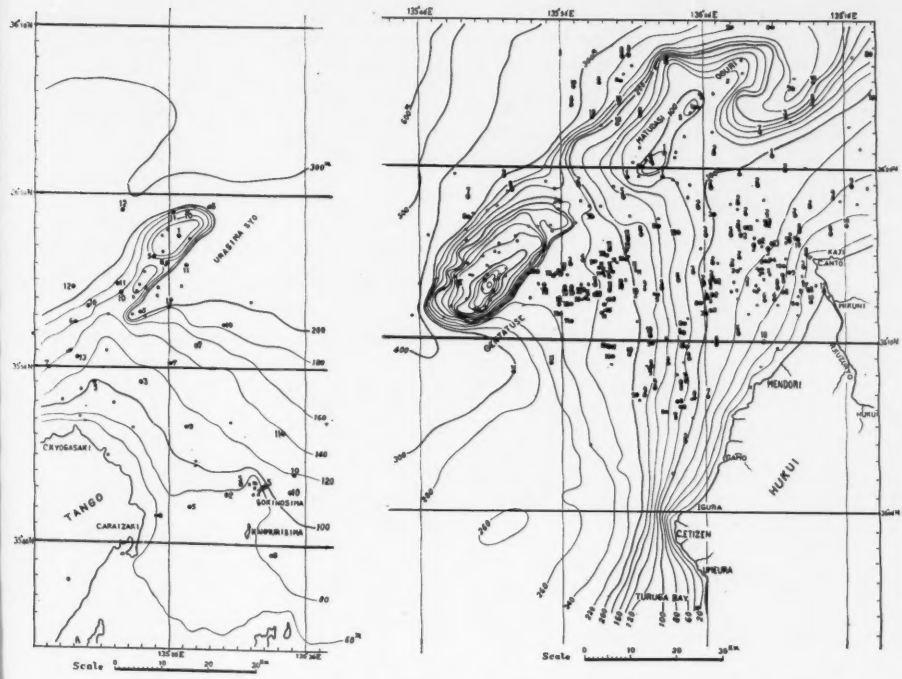


FIG. 5.—Map showing distribution of the different types of cumulative curves at various stations.

sand is less than 50 per cent of the total are restricted to either the mouth of the river or to depressed areas outside the continental shelf. Sand found at the points where gravel was obtained or where the sea floor is exposed is generally coarse. The factors which determined the distribution of sediments can be summarized as:

a. *Rocky floor.*—The distribution of rocky bottoms is governed by the submarine topography which in turn depends upon crustal movement. The rock floor is then covered by subsequent sediments, whose thickness depends upon the pre-existing topography and the strength of the oceanic current.

b. *Gravel.*—On the basis of the time of origin, gravel can be classified into old and new. The distribution of old gravel is governed by submarine topography, while that of the new gravel on the banks and their surroundings is determined by the bottom current. Such gravel is found co-mingled to some extent with that which was washed out of the old gravel bed on the bottom and these occur even in the deep marginal zones around the banks. The distribution of gravel at the mouth of rivers and near the coast is determined by the strength of the river current and of the waves.

c. *Sand and mud.*—Like gravels there are old and new sand and mud deposits, which, according to their grain size, are classified into those coarser or finer than

0.295–0.147 mm. The distribution of the coarser ones is controlled by topography while that of finer ones depends on the strength of currents. The distribution of mud assumes a peculiar aspect off the mouths of the rivers. Generally sand and mud on the sea bottom change gradually from coarse to fine as depth increases but on some elevations like banks and their surroundings, the sediment is much coarser than on the shelf at the same depth.

DISTRIBUTION OF ORGANISMS

General

Excluding microorganisms, it was found that macroorganisms were contained in the bottom samples from 258 stations from the total of 623. More precisely, 154 species of Pelecypoda were found at 222 stations, 168 of Gastropoda at 159, 16 of Scaphopoda at 82, 3 of Pteropoda at 27, 21 of Crustacea at 37, 21 of Echinodermata at 64, 3 of Bryozoa at 37 (specific names unknown), 2 of Annelida at 16, and Porifera at 12. In addition, algae exclusive of calcareous algae but including 5 species of Chlorophyceae, 17 of Phaeophyceae, 10 of Rhodophyceae, and 1 of Phanerogamaceae were found at 1, land plants at 15, shark teeth at 3, otolith of whale at 1, and fish at several stations. Molluscs were most numerous both in number of individuals and species, and were found at more stations than the other groups. The ratios of the number of stations where these groups of organisms were found to the total number of stations which yielded them are:

	Per cent
Pelecypoda	87.7
Gastropoda	61.6
Scaphopoda	31.8
Pteropoda	10.4
Brachiopoda	28.3
Porifera	4.6
Anthozoa	35.0
Echinodermata	24.8
Bryozoa	14.3
Hydrozoa	1.1
Annelida	6.2
Algae exclusive of calcareous Algae	7.0

Each of these groups of organisms reveals characteristics in its distribution which generally are related closely to the depth and bottom condition. The influence of these factors is notable in the distribution of Brachiopoda and Bryozoa. While the bottom condition is a definite factor enabling algae to flourish, the distribution of land plants depends principally upon the amount of water flowing into the sea from the rivers.

Relationship of Organisms to Depth

Classifying the sea floor into bathymetric zones, each of 20 meters depth, the following was calculated for each zone; (a) the ratio of the number of stations where organisms were found to the total of the stations where samples were obtained; (b) the ratio of the number of stations in each depth zone where organisms were found to the total of the stations where organisms were found; (c) the ratio of the specific number of organisms in each group to the total of the biota recognized in the bottom sample; and (d) the number of species of each biological group on an average per station in each zone.

The (a) calculation gave 38 per cent for 0–20 m, 5.4 per cent for 20–40 m, 6.2 per cent for 40–60 m. 13.9 per cent for 60–80 m, 20.9 per cent for 80–100 m, 20.5 per cent for 120–140 m, 7.3 per cent for 140–160 m, 3.1 per cent for 160–180 m, 3.1 per cent for 180–200 m, 1.5 per cent for 200–220 m, 4.6 per cent for 220–240 m, 0.7 per cent for 240–260 m, 1.1 per cent for 260–280 m, and 0.3 per cent for 280–300 m.

The proportion of the number of stations which yielded a sample of a faunal group within each depth range to the total of stations yielding samples of that fauna (b calculation) remains approximately the same for all faunal groups. Roughly speaking, samples of all faunal groups were mostly from the range of 80–100 m or from 100–120 m.

The total or average number of species does not always vary with the number

TABLE 1.—*Organisms other than Mollusca, listed in decreasing order according to the total number of stations yielding organisms within each 20 meter depth range*

Depth in Meters	Order			
	1	2	3	4
0– 20	Echinodermata	Crustacea		
20– 40	Echinodermata	Crustacea	Anthozoa	Brachiopoda
40– 60	Anthozoa	Echinodermata	Crustacea	Bryozoa
60– 80	Anthozoa	Brachiopoda	Echinodermata	Crustacea
80–100	Anthozoa	Brachiopoda	Echinodermata	Crustacea
100–120	Anthozoa	Brachiopoda	Echinodermata	Crustacea
120–140	Anthozoa	Brachiopoda	Echinodermata	Crustacea
140–160	Brachiopoda	Anthozoa	Echinodermata	Crustacea
160–180	Brachiopoda	Anthozoa	Echinodermata	Crustacea
180–200	Brachiopoda	Echinodermata	Anthozoa	Crustacea
200–220	Echinodermata			
220–240	Anthozoa	Echinodermata	Brachiopoda	Crustacea

TABLE 2.—*Mollusca, listed in decreasing order according to the proportion of the number of stations where each family was collected, to the total of stations yielding Mollusca within each 20 meter depth range*

Depth in Meters	Order			
	1	2	3	4
0– 20	Pelecypoda	Gastropoda	Scaphopoda	Pteropoda
20– 40	Pelecypoda	Gastropoda	Scaphopoda	Pteropoda
40– 60	Pelecypoda	Gastropoda	Scaphopoda	Pteropoda
60– 80	Pelecypoda	Gastropoda	Scaphopoda	Pteropoda
80–100	Pelecypoda	Gastropoda	Scaphopoda	Pteropoda
100–120	Pelecypoda	Gastropoda	Scaphopoda	Pteropoda
120–140	Pelecypoda	Gastropoda	Scaphopoda	Pteropoda
140–160	Pelecypoda	Scaphopoda	Gastropoda	
160–180	Pelecypoda	Gastropoda	Scaphopoda	
180–200	Pelecypoda	Gastropoda	Scaphopoda	
200–220	Scaphopoda	Pelecypoda	Gastropoda	
220–240	Pelecypoda	Gastropoda	Scaphopoda	
240–260	Gastropoda	Scaphopoda		
260–280	Pelecypoda	Gastropoda		
280–300	Scaphopoda			

or total number of stations. Among the biological groups, molluscs were found at the largest number of stations in each zone. Among the molluscs, Pelecypoda were most abundant, followed by Gastropoda, Scaphopoda, and Pteropoda. Among other organisms the distribution of Brachiopoda and Anthozoa is intimately related to the depth. (See tables 1, 2, 3.)

Relationship of Organisms to Character of Bottom

Bottom samples at hand were classified into eleven kinds: R, RG, RGS, RGM, RS, RM, G, GS, GM, S, and M, where R stands for rock, G for gravel, S for sand, and M for mud. The ratio of the number of organism bearing samples to the total number of samples in each kind of bottom was calculated. The re-

TABLE 3.—*Average number of species for each group of organisms per station for the first four 20-meter depth-ranges yielding the highest averages*

Organism	Order							
	1		2		3		4	
	Depth	Species	Depth	Species	Depth	Species	Depth	Species
Pelecypoda	40– 60	4.7	120–140	2.7	180–200	2.5	20– 40	2.2
Gastropoda	40– 60	4.7	60– 80	3.0	200–220	3.0	20– 40	2.9
Scaphopoda	220–240	2.0	200–220	1.5	80–100	1.0	240–260	1.0
Pteropoda	120–140	0.5	20– 40	0.3	40– 60	0.3	60– 80	0.2
Brachiopoda	80–100	4.4	20– 40	4.0	120–140	1.4	160–180	1.0
Anthozoa	100–120	4.4	180–200	3.0	40– 60	1.8	20– 40	1.0
Crustacea	120–140	7.1	160–180	2.0	180–200	2.0	60– 80	1.7
Echinodermata	140–160	1.5	0– 20	1.0	20– 40	1.0	80–100	1.0

TABLE 4.—*Proportion of the number of stations yielding a group to the number of stations yielding organisms, calculated for various classes of bottom materials*

Organism	Order							
	1		2		3		4	
	Bottom[1]	Per Cent	Bottom[1]	Per Cent	Bottom[1]	Per Cent	Bottom[1]	Per Cent
Pelecypoda	GS	38.6	S	15.0	M	11.7	RGS	10.8
Gastropoda	GS	35.0	RGS	15.2	M	11.2	S	10.6
Scaphopoda	GS	40.1	M	15.3	RGS	11.5	GM	7.7
Pteropoda	GS	60.8	RGS	13.0	M	13.0	RG	4.3
Brachiopoda	GS	29.5	RGS	23.9	R	9.8	RGM	9.8
Anthozoa	GS	27.0	RGS	18.9	RG	15.2	RGM	10.7
Echinodermata	GS	30.3	RG	19.6	R	12.5	RGS	10.7
Crustacea	RG	26.4	RGS	20.5	GS	17.3	RGM	14.6
Hydrozoa	RGS	33.3	GM	33.3	M	33.3		
Porifera	R	25.0	RGS	25.0	M	16.6	RG	13.2
Annelida	G	31.2	RM	17.5	RS	12.5	GM	12.5
Algae	R	11.7	RGS	11.7	RG	11.7	RS	11.7

[1] Bottom materials key: R = rock; G = gravel; S = sand; M = mud.

sult obtained is: R (5.74 per cent), RGS (10.2 per cent), RGM (4.0 per cent), RG (6.1 per cent), RS (1.6 per cent), RM (0.8 per cent), G (2.4 per cent), GS (3.6 per cent, GM (4.8 per cent), S (13.8 per cent), M (13.4 per cent).

Comparison of Distribution of Organisms on Continental Shelf and Bank

Bottom samples with organisms collected with the aid of Kamiya's dredge were grouped for every 20 meters increase in depth. The dredged points are few on the banks between the depths of 0 and 60 m, while on the shelf they are extremely numerous in the same bathymetric range but much less in number than on the banks in depths greater than 180 m. Therefore comparison was made only among the material dredged from the depths between 60 and 180 m. The number of species as well as of individuals in the same bathymetric range are far larger on bank than on the shelf. It must, however, be noted that bottom

TABLE 5.—*Organisms listed in the order of the number of stations yielding them for each bottom of different character*

Bottom Character[1]	Order					
	1	2	3	4	5	6
R	Pelecypoda	Gastropoda	Brachiopoda	Anthozoa	Echinodermata	Bryozoa
RGS	Pelecypoda	Gastropoda	Anthozoa	Brachiopoda	Bryozoa	Scaphopoda
RGM	Anthozoa	Pelecypoda	Gastropoda	Brachiopoda	Echinodermata	Scaphopoda
RG	Pelecypoda	Anthozoa	Echinodermata	Gastropoda	Brachiopoda	Scahpopoda
RS	Pelecypoda	Gastropoda	Anthozoa	Bryozoa	Crustacea	Scaphopoda
RM	Pelecypoda					
G	Pelecypoda	Gastropoda	Anthozoa	Bryozoa	Crustacea	Scaphopoda
GS	Pelecypoda	Gastropoda	Scaphopoda	Anthozoa	Brachiopoda	Echinodermata
GM	Pelecypoda	Gastropoda	Crustacea	Scaphopoda	Anthozoa	Brachiopoda
S	Pelecypoda	Gastropoda	Scaphopoda	Brachiopoda	Echinodermata	Anthozoa
M	Pelecypoda	Gastropoda	Scaphopoda	Pteropoda	Anthozoa	Echinodermata

[1] Bottom material key: R=rock; G=gravel; S=sand; M=mud.

TABLE 6.—*The number of species of the various organisms listed according to the bottoms of different character*[1]

Organism	Order							
	1		2		3		4	
	Bottom	Species	Bottom	Species	Bottom	Species	Bottom	Species
Pelecypoda	G	9.8	RG	4.1	R	4.0	RGS	2.8
Gastropoda	RS	4.2	R	4.0	G	4.2	S	2.8
Scaphopoda	GS	3.3	RG	2.0	RS	2.0	G	2.0
Pteropoda	RG	1.0	G	1.0	RGS	0.6	M	0.3
Brachiopoda	G	6.0	GS	3.8	S	2.5	R	1.4
Anthozoa	S	2.5	RS	2.5	G	2.3	R	1.4
Echinodermata	G	2.0	GM	1.5	RGS	1.0	RGM	1.0
Crustacea	R	2.6	G	2.0	RGS	1.5	M	1.0

[1] Bottom material key: R=rock; G=gravel; S=sand; M=mud

samples are basement rocks, gravels, and sands on the banks, but on the shelf gravels, sand, and mud are common. The distribution of organisms is thus effected by the nature of the sea bottom. A comparative study was carried out on the same kind of bottom samples, as tabulated below. Only RGS and GS samples

Depths	Bottom character	Shelf	Bank
80–100 m	S	1 point	1 point
100–120 m	RGS	5 points	2 points
120–140 m	GM	2 points	2 points
140–160 m	GS	1 point	11 points
160–180 m	RGS	1 point	2 points

were obtained in the depths between 100 and 120 m, if more than two points common between the shelf and banks are selected. Therefore, unless more dredging is carried out, no definite conclusion from such a comparison can be drawn, but it is notable that the number of species is greater on the banks than on the shelf.

With the material at hand it was found that the Mollusca are abundant both on the shelf and banks while the Scaphopoda are common on the shelf but uncommon on the banks, except in the bathymetric range of 140 to 160 m. The average number of Pelecypoda species at each point is greater on the banks than on the shelf, but the number is about the same for the Gastropoda. Brachiopoda, Anthozoa, and Crustacea were found at more points on the shelf and the number of their species is also greater there. An-

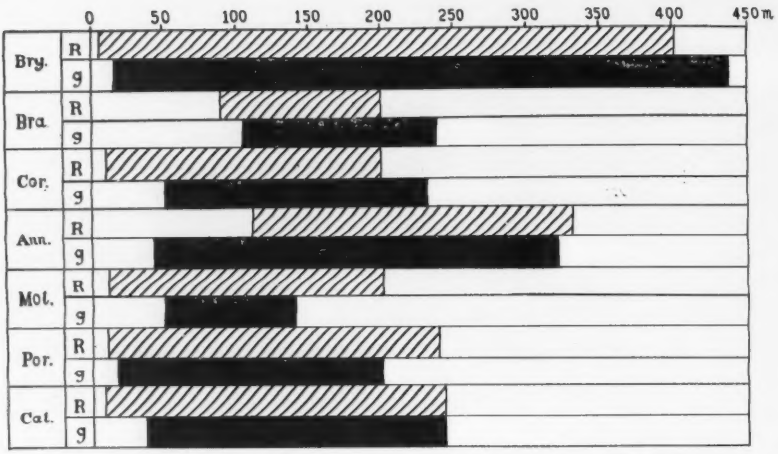


FIG. 6.—Depth range of distribution of organisms attached to rocks and gravel. Key: R = rock; G = gravel; Bry = Bryozoa; Bra = Brachiopoda; Cor = Coral; Ann = Annelida; Mol = Mollusca; Por = Porifera; Cal = calcareous Algae.

nelida, Bryozoa and some other groups of organisms were found only on the banks. Generally, the same species is distributed in a much wider bathymetric range on banks than on the shelf as exemplified by the following four species:

Species	Bathymetric Range in Meters	
	Bank	Shelf
Ostrea musashiana Yokoyama	58–236	21–159
Cardita ferruginea (A. Adams)	38–230	22–123
Limopsis crenata A. Adams	50–276	22–132
Chlamys vesiculosa (Dunker)	58–199	44–140

Relationship of Organisms to Temperature

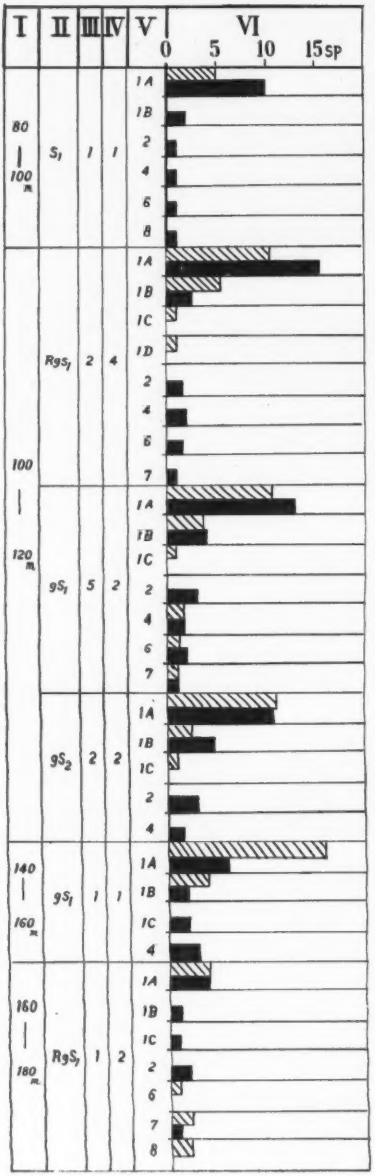
In this study, animals and plants occurring in Central Japan were not taken up and only the boreal and austral organisms were given consideration. Austral or warm water forms comprised 11 species of Pelecypoda, 6 of Gastropoda, 1 of Anthozoa, and 1 of Algae. Among the 63 stations containing austral organisms, 25 contained no boreal forms. At most stations where both kinds of forms were found together the number of the austral exceeded that of the boreal forms, while at 13 stations the number was the same for both kinds.

The austral forms are mostly found in the shallow part on the banks and in the vicinity of capes. The boreal ones occur on the slope of the shelf and on the banks. The number of species of organisms of the two kinds are generally about the same on banks. On the shelf and the banks off the shore, boreal species are more numerous than austral ones; the reverse is found in the cape region and in the shallow part of the banks.

TABLE 7.—*The distribution range of depth and temperature of organisms of cold and austral type*

	Depth in Meters	Temperature Degrees C.
(a) Austral type		
Pelecypoda		
Aloides rotalis (Hinds)	74– 95	11.3– 19.8
Aloides scaphoides (Hinds)	50–136	13.8– 28.6
Crassatelites nanus (Adams and Reeve)	43–119	22.0– 27.9
Chione mindanaeasis Philippi	70–111	12.4– 21.5
Limopsis multistrata (Forskål)	39–123	14.0– 28.6
Cardila ferruginosa (Adams and Reeve)	78	22.0
Gastropoda		
Nassarius gemmulatus (Lamarck)	29– 45	25.5– 25.7
Phalium japonicum (Reeve)	21–104	14.8– 28.2
Strombus japonicus Reeve	62	20.9
Umbonium moniliferum costatum (Kiener)	25– 45	25.5– 25.7
Brachiopoda		
Campages basilanica Dall	58–121	10.6– 19.4
(b) Cold water type		
Pelecypoda		
Acila divaricata (Hinds)	62–273	1.6– 26.2
Astarte alaskensis Dall	108–199	8.0– 17.3
Astarte borealis Schumacher	78–199	5.6– 22.0
Glycymeris vessoensis (Sowerby)	59–150	8.0– 28.0
Limopsis pelagica Smith	76–199	3.6– 26.9
Limopsis azumana Yokoyama	115–190	8.0– 15.6
Lucinoma acutilineata (Conrad)	148–163	5.5– 11.2
Nucula tenuis Montague	73–170	8.0– 23.8
Chlamys swiftii (Bernardi)	55–119	13.2– 19.0
Solen kurusensterni Schumacher	21–140	15.8– 28.1
Hiatella arctica (Linné)	27–199	4.8– 28.1
Gastropoda		
Ancistolepis fujitai Kuroda	194	5.6
Fusitrition oregonensis (Redfield)	58–199	5.5– 18.6
Natica clausa Broderip and Sowerby	60–237	1.0– 23.8
Polinices draconis Dall	21–148	11.0– 28.1
Solariella angulata Tokunaga	78–135	12.4– 22.0
Solariella peramabilis pseudobuscura Yokoyama	62–123	12.4– 22.0
Coral		
Dendrophyllia japonica Erhenberg	89–142	9.7– 26.6
Crustacea		
Screlocrangon gasuyebi Yokoya	194–239	0.8– 5.6
Echinodermata		
Psolus japonica Ostergren	133–158	4.8– 13.0
Rhodophyceae		
Callymenia reniformis J. Agassiz	50– 76	17.2– 22.3

The average depth of stations grouped according to organisms comprised is: (1) stations of warm water forms only, 72.2 m, (2) stations of cold water forms only, 137.0 m, (3) stations where both kinds of forms were found together, the austral forms exceeding the cold forms, 45.6 m, (4) stations where both kinds of forms were found together, the number of species being the same for both kinds, 78.6 m. Thus, warm water forms are distributed in the shallow bottoms of the cape region, as may be expected from the oceanic current. The coexistence of the two forms around the bank may be due to the hydrographic condition complicated by the upwelling of the bottom current and of the surface current.



Characteristic Distribution of the Several Groups of Organisms

Pelecypoda were most abundant at 54 stations in the bathymetric range from 80 to 100 m and their specific number was largest between 100 and 120 m. They were especially abundant in GS; Gastropoda were most numerous at 100–120 m. Scaphopoda occur on the shelf in the main and between 100 and 120 m and prefer to live in GS and M. Pteropoda are more or less common in the shallow part.

Brachiopoda are most abundant in 100–120 m. Their specific number reaches a maximum between 120–140 m. They appear to thrive in GS and RGS.

Anthozoa were found most commonly between 100–120 m in which range their specific number is greatest. GS appears to be the best environment.

Aqueous Phanerogamae were found only near Cape Arai-zaki, among Algae exclusive of calcareous algae; 5 species of Chorophyceae, 17 of Phaeophyceae, and 10 of Rhodophyceae were found at

FIG. 7.—Comparison of the number of species on the banks and the Continental Shelf, at the same depth range and from bottom of the same material.

LEGEND FOR FIGURE 7

I Depth
II Bottom material
R rock
g gravel
S_1 sand
S_2 mud
III Number of stations on the Continental Shelf
IV Number of stations on the bank
V Kind of organism
1A Pelecypoda
1B Gastropoda
1C Scaphopoda
2 Brachiopoda
3 Bryozoa
4 Anthozoa
5 Hydrozoa
6 Echinodermata
7 Crustacea
8 Annelida

numerous stations between the depths of 40 and 60 m and the lower limit of distribution of Rhodophyceae is 80 m and that of Phaeophyceae, 199 m.

Wood stems, stems of bamboo and plant leaves, were found clustered in the shallow, estuarine places at the mouth of the Kuzuryu River in depths of 8–59 m. They are commonly contained in GS. Incidentally they were found also on the shelf between Okinoshima and Arai-zaki.

CONCLUSIONS

The studies of the bottom samples from the banks and continental shelf in Wakasa Bay, as well as investigations on the geology of the adjacent coastal region, have shown that both the nature of shallow sea deposits and their distribution are affected, not only by the depth of the sea, but also by topography, geological history, and hydrographic conditions.

While the abnormal distribution of gravel and coarse sand in the deposits of the continental shelf can be explained with reference to the geological history of the shelf, the distribution of fine sand and mud depends on the depth of the sea, topography, oceanic currents, and the supply of sediment from the rivers.

The banks are partly rocky and partly covered with gravel, sand, and mud. The banks off the coast were isolated from the main island and submerged by post-Tertiary crustal movement. This can be readily understood from their topography and the rocks and fossils collected from them. Numerous banks aligned along the coast of the Japan Sea are of the same origin.

The sediments of the banks and surroundings are quite different from those on the adjoining shelf in their nature and distribution, in the number of species and organisms, as well as in the aspect of the biota, even when those of the same depth on the banks and shelf are compared.

The marine sedimentary rocks are mostly shallow sea sediments. Such sediment accounts for the larger part of the Tertiary formations in Japan which present a rich variety of rock facies and faunae. The correlation of these formations is thus rendered difficult. It is quite reasonable to consider that the variation of shallow sea sediments and the contained organisms as seen in Wakasa Bay at present, has existed from the geological past. Therefore, it is quite certain that a study of present sediments yields information on various past problems of stratigraphy.

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FIGS. 1–6, APRIL, 1950

DIASTEMS IN THE PECAN GAP CHALK OF TRAVIS COUNTY, TEXAS

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ABSTRACT

The importance of the recognition of diastems, in attempts at detailed microfaunal zonation of marine strata, is discussed. Three diastems are described, occurring in an exposure of Pecan Gap chalk (Upper Cretaceous, Taylor group) near Austin, Texas. The presence of encrusting foraminifera on casts of mollusks is indicated as evidence for the existence of a diastem.

INTRODUCTION

Diastems are discontinuities in sedimentation within marine formations, due to interruption of deposition or to nearly contemporaneous erosion without elevation above sea-level (Barrell, 1917, p. 794). Probably these intra-formational hiatuses are more common in shelf deposits, such as those of the Gulf Coast of the United States, than in the rapidly deposited "basin type" rocks of the West Coast of North and South America (compare Dapples, Krumbein, and Sloss, 1948). Although diastems are well recognized sedimentary phenomena (Twenhofel, 1932, pp. 106–108), information about their presence in the rocks of the United States is scant. American stratigraphers have given little attention to the position and interpretation of diastems, possibly because of the difficulty of recognizing and evaluating hiatuses that are indicated neither by gross changes in lithology nor by marked erosional surfaces.

This note is intended to record three previously unrecognized diastems within the Pecan Gap chalk (Upper Cretaceous, Taylor group) of central Texas, to call attention to a faunal criterion for recognizing such intra-formational breaks, and to point out some of the biostratigraphic implications of intra-formational hiatuses. Inasmuch as these observations are a byproduct of our studies of Cretaceous foraminifera, we have made no more than a cursory examination of literature on this aspect of sedimentation.

LOCATION AND DESCRIPTION OF OUTCROP

The outcrop to be described is situated about 3.5 miles east of the city limits of Austin, Travis County, Texas, in a road-cut along Texas State Highway 20. The cut is 0.4 mile east of a Missouri, Kansas, and Texas Railroad overpass, on a section of the highway that was completed early in 1948. (See sketch map, fig. 1.) In this area northeasterly trending bands of Upper Cretaceous strata are exposed, ranging from the Austin chalk (Austin group), at Austin, through the Taylor and Navarro groups, with some units missing (Adkins, 1932; Ellisor and Teagle, 1934; Stephenson, 1936). The Pecan Gap chalk is the middle unit of the Taylor group in this section, with argillaceous marls above and below.

The formation at this exposure is a buff chalky marl, soft and moderately weathered, eroding very rapidly. Foraminifera and *Inoceramus* prisms make up a large part of the rock. Megafossils, chiefly molluscan, occur sparsely and sporadically throughout most of the sec-

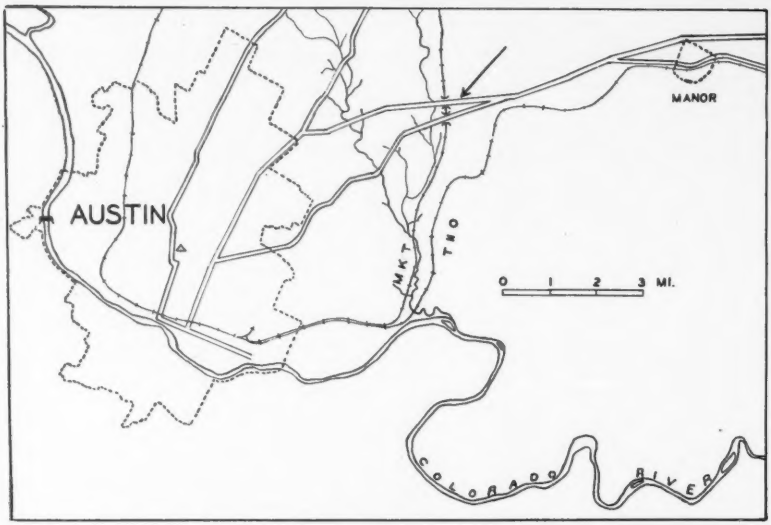


FIG. 1.—Sketch map of part of Travis County, Texas. Arrow shows location of outcrop of Pecan Gap chalk with diastems.

tion, as well as in occasional concentrated layers. More than 27 feet of strata are exposed. The relation of the Pecan Gap chalk to the subjacent lower Taylor marl is not clear, but the contact probably is disconformable.

Three shelly layers, considered to be diastems, are present in the exposure (fig. 6). Near the base is a thin band marked by abundant molluscan shells and casts, including sparse baculites. About ten feet higher is a second fossiliferous layer, the fossils consisting largely of casts of baculites, but including other mollusks and a few vertebrate remains. Many of the shells, especially the baculites, are broken. With them are mosasaur bones, reptilian (or amphibian?) remains, shark teeth, and crocodile plates. A third layer of abundant shells appears in the western end of the exposure, about four feet above the second, paralleling it for some 300 feet and merging with it near the eastern end of the outcrop. The marl above, below, and in the wedge between these layers appears to be identical in lithic characteristics. The layers themselves differ from the adjacent marl only in the concentration of organic remains.

EVIDENCE FOR THE PRESENCE OF DIASTEMS

The presence of a wedge of strata, separated by layers with concentrated and largely fragmental megafossils, is believed to be good evidence for postulating intra-formational hiatuses above and below the wedge. The layers themselves may be regarded as intra-formational conglomerates in which the megafossils are residual elements.

The strongest evidence for diastems in the Pecan Gap exposure is faunal: encrusting foraminifera have been found cemented to casts (fig. 5), as well as to perfectly preserved shells and other organic debris, at all three levels. There is no evidence of reworking from an older formation, and the megafossils are generally accepted as endemic to the strata in which they occur. More than 200 exam-

ples have been noted in samples from the shelly layers, so the relationship of encrusting foraminifer to molluscan cast cannot be regarded as fortuitous or due to errors of observation.

A very rough estimate of the thickness of sediments missing in these diastems may be made from the concentration of shells in comparison to the occurrence of megafossils in the normal section. We believe that the lower and upper diastems represent a conservative minimum of ten feet of sediments, the middle possibly as much as twenty or more. If this hypothesis is correct, these hiatuses would account for much of the thinning of the Pecan Gap chalk in central Texas.

ENCRUSTING FORAMINIFERA AS INDICATORS OF DIASTEMS

Encrusting foraminifera belong to a number of diverse families, but have in common the habit of cementing their tests to the coarser bottom debris. Several examples are illustrated in figures 2 to 5. These organisms required a firm base, having been unable to live on soft mud or ooze. Consequently, they attached themselves to mollusk shells, echinoid spines and plates, pebbles, and other durable miscellanea of the sea-floor. Our observations, on encrusting forms ranging in age from Lower Cretaceous to Paleocene, show that the relationship of test and solid base is invariable.

The growth of encrusting foraminifera on casts, except for the obvious case of reworked fossils, demonstrates the formation of diastems through the following steps: (1) burial and filling of the shells; (2) deposition of some overburden of sediments; (3) cementing of the mud filling (with or without compaction); (4) erosion and redeposition of the shells (possibly deflationary current action rather than transportation); (5) attachment of encrusting foraminifera; (6) renewal of deposition.

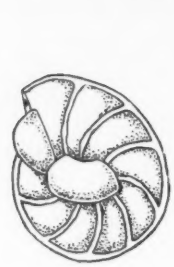
BIOSTRATIGRAPHIC SIGNIFICANCE OF DIASTEMS

Confusion is inevitable when lithogenetic units are made the primary basis for correlation. The principle of temporal transgression (Wheeler and Beesley, 1948) applies to all formations, and prevents the precise synchronization of formations and members. Formational boundaries cross time planes, and formational equivalence is at best no more than very roughly approximate. The results of correlating lithogenetic units, in the Cretaceous sequence of Texas and the Gulf Coast area, may be seen in accounts of the Pecan Gap chalk (Ellisor and Teagle, 1934; Stephenson, 1936), the Woodbine sand and Eagle Ford shale (Lozo, 1948), and formations of the Fredericksburg group (Stephenson and others, 1942).

The logical alternative to correlation by formational units is the biostratigraphic use of stages and zones (see discussions by Kleinpell, 1938, and Moore, 1948). If this premise is accepted, recognition of diastems assumes more than academic importance. The biostratigraphic approach to correlation demands detailed study of continuous stratigraphic sections, so that the succession of microfaunal assemblages may be established. Where sections are interrupted, they must be overlapped and pieced together. As Barrell (1917, p. 794) pointed out, diastems presumably are of local extent, and the gaps may be filled from adjacent sections.

Application of these principles to the Pecan Gap exposure is shown in figure 6. Lacking evidence of the diastems, one would accept the equivalence of segments B, C, and D with segments E and F. Differences in sequence of microfaunas would be attributed to lateral variation. Recognition of the diastems, however, shows that, although both sections are incomplete, section I contains beds that are missing in section II.

Lateral variation in microfaunal assemblages is to be expected. It may be due to local environmental factors, to sporadic distribution, or to sampling error. The existence of one or more diastems, however, may lead to an entirely



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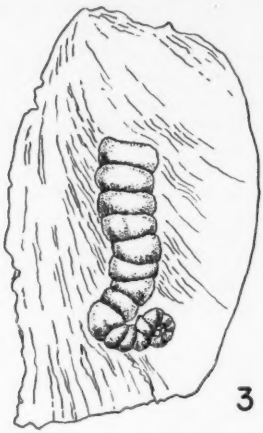

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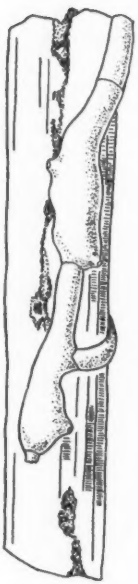

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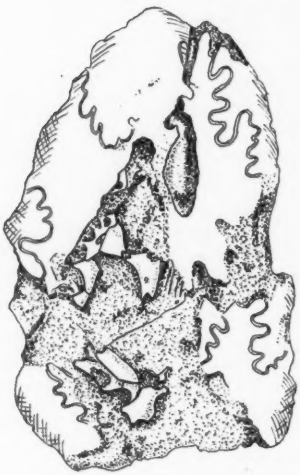

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FIGS. 2–5.—Encrusting foraminifera. Sketches considerably enlarged, but at various magnifications. 2. *Bullopora chapmani* (Plummer) in normal position on a specimen of *Robulus midwayensis* (Plummer); lower part of Midway group (Paleocene). 3. *Acruliammina longa* (Tappan) in normal position on a pelecypod fragment; Del Rio clay (Lower Cretaceous, Washita group). 4. *Bullopora* n. sp. in normal position on an echinoid spine; lower Taylor marl (Upper Cretaceous, Taylor group). 5. *Bullopora* n. sp. encrusting on eroded surface of a baculite cast; Pecan Gap chalk (Upper Cretaceous, Taylor group).

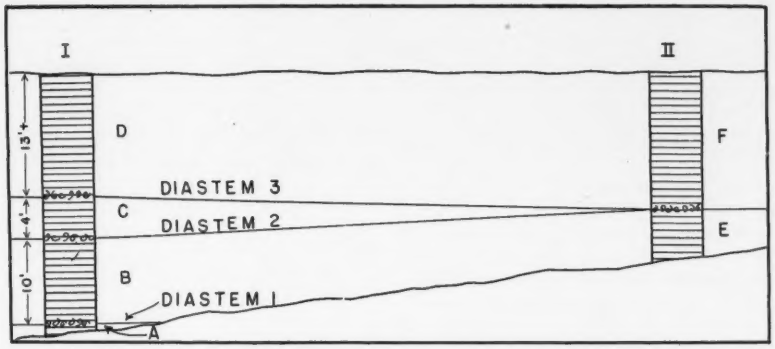

FIG. 6.—Diagrammatic sketch of the Pecan Gap exposure, showing position of diastems and relationship of adjacent strata.

erroneous interpretation of differences in apparently synchronous beds. Minute search for both physical and faunal evidence of diastems, therefore, is prerequisite to any attempt at detailed microfaunal zonation.

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APRIL, 1950

REVIEW

The Study of Rocks. By S. J. Shand. Pp. 236. Thomas Murby and Co., London, Second Edition, Revised, 1947. Price, 10s6d.

The first edition of this book appeared in 1931, and the general outline and treatment remain essentially the same in the second edition. Without appreciable enlargement the work has been revised and is now more up-to-date. Some supplementary material has been added and the appendix on chemical analysis of rocks has been lengthened to good advantage.

Although the book is largely descriptive, considerable attention is given to petrogenetic problems. This is remarkably well done when one considers the brevity of the text. Unlike many authors, Dr. Shand has attempted to point out and emphasize the most important side of rock study—in the field.

The three classes of rocks—igneous, sedimentary and metamorphic—are considered in turn and Shand's classification determines the order of treatment within each class. The chapters on rock descriptions include mineral content, textures, structures and geological occurrence of rocks. Examples of each rock type are given from well-known and classical areas.

It may appear, at first glance, that undue emphasis is given the igneous rocks as over half the book is devoted to this class. It should be noted, however, that considerable attention must be given to the old and complicated problem of nomenclature and classification which involves greater differences of opinion than is true of the sedimentary and metamorphic rocks. Furthermore, the chapter on composition of eruptive rocks discusses the igneous rock-forming minerals and many of these constitute the major mineral components of the other classes of rocks as well. It is not surprising but, perhaps, to be desired that Dr. Shand should focus more attention on the rock class of which he is an outstanding authority.

The treatment of sedimentary rocks, covered in 48 pages, is brief but is relatively quite complete. The varieties are described under four headings; organic residues, residues from solution, crystalline rock residues, and cryptocrystalline and colloidal rock residues. Considerable information as to genesis is included here.

Many suggested readings at the end of each chapter furnish the student with a list of some of the more valuable references on petrology and petrography. These references serve to introduce the student to the literature and enable him to obtain further information on a wide variety of selected subjects.

A tremendous amount of material has been condensed in this 236 page volume and the style of writing is easy to read.

It is suggested that the addition of more material on structures and microstructures of rocks and a somewhat more extended treatment of rock-forming minerals would have justified the additional space required and added greatly to the usefulness of the text.

This book can be understood by one who has completed an elementary course in geology, and it is well worth the attention of even the much more advanced student. It is ideal for one desiring a brief but rather thorough and accurate review of the field of rock study.

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